Part 3

7. IMPEDIMENTS TO FLUVIAL DELIVERY OF SEDIMENT TO THE SHORELINE

7.1 Introduction

Sediment budget studies have estimated that coastal rivers and streams supply, on average, 70 to 90% of beach sand in California (Bowen and Inman, 1966; Best and Griggs, 1991). Accompanying the explosive growth and land use change in California's coastal watersheds over the twentieth century, 480 major dams and reservoirs, nearly 200 debris basins, hundreds of in-stream sand and gravel extraction operations (Kaufman and Pilkey, 1979; Brownlie and Taylor, 1981), and hundreds of miles of stream bank and bed channelization have reduced fluvial sediment transport to a fraction of natural rates. Rates and magnitudes of fluvial sediment delivery have been altered significantly from long-term natural rates by the construction of barriers to sediment transport and land use changes that have modified watershed erosion rates (i.e. sediment production). This report makes a substantive effort to quantify the reduction in sediment supplied to the coast due to the impacts of major dams, debris basins, and channelized streams. Alterations in watershed sediment yield due to land-use changes and the effects of in-stream sediment mining are not addressed in this report but are important topics for future research.

7.1.1 Overview

Sediment is delivered to the river and stream channel by basin erosion processes including hill slope creep, overland flow, landslides, and debris flows. Once delivered to the channel, sediment is transported down the channel network as dissolved or solid load. Solid load, the dominant mode of fluvial transport in California, includes both suspended sediment—sediment that it is fully entrained in the moving water column—and bedload—coarser material that rolls or bounces along the stream bed. About 85 to 95% of all sediment is carried as suspended load; however, only 10 to 38% of this sediment is sand-size material (grain diameter between 0.062 and 2.00 mm) that could contribute to beach supplies. Bedload, which typically ranges from 5 to 15% of the total sediment load (Collins and Dunne, 1990; Inman and Jenkins, 1999), is comprised almost entirely of sand- or larger-size sediment. The amount of sediment in transport at any given time depends on both the magnitude of stream flow and grain size of sediment present on the streambed. Basin relief, the magnitude and intensity of precipitation events, antecedent rainfall conditions, soil and underlying bedrock types, density of vegetation, and land-use are among the important climatic and geologic variables that determine the magnitude of stream flows and the types of sediment present on the stream bed. Sediment in transport in coastal fluvial systems ultimately will be stored within the basin—either in the stream channel, in the flood plain adjacent to the stream, or in an estuary at the stream mouth—or it will be delivered directly to the ocean. When sediment is delivered to the coast, the fine silts and clays are quickly moved offshore by wind- and wave-generated currents, while the sands and gravels are deposited near the river mouth as beach or delta deposits, which are available for transport along the coast by longshore currents.

California's coastal watersheds are of two general types: (1) the steep, erodible, conifer-forested Coast Range basins north of Monterey Bay, which are characterized by high seasonal rainfall and perennial streams, and (2) the more arid basins of Central and Southern California, which often drain chaparral- or grassland-covered headwaters, but may cross broad alluvial valleys in the their lower reaches. On average, the state's coastal watersheds receive 82% of the annual precipitation between November and March (National Climate Data Center, 2001). As a result, almost all sediment is brought to the coast during storms over these winter months. Northern California, depicted in Figure 7.1 as Division 1, receives an average of 42 inches of rain annually, while Central and Southern California (Divisions 4 and 6) receive annual averages of 21 and 17 inches, respectively (National Climate Data Center, 2001).

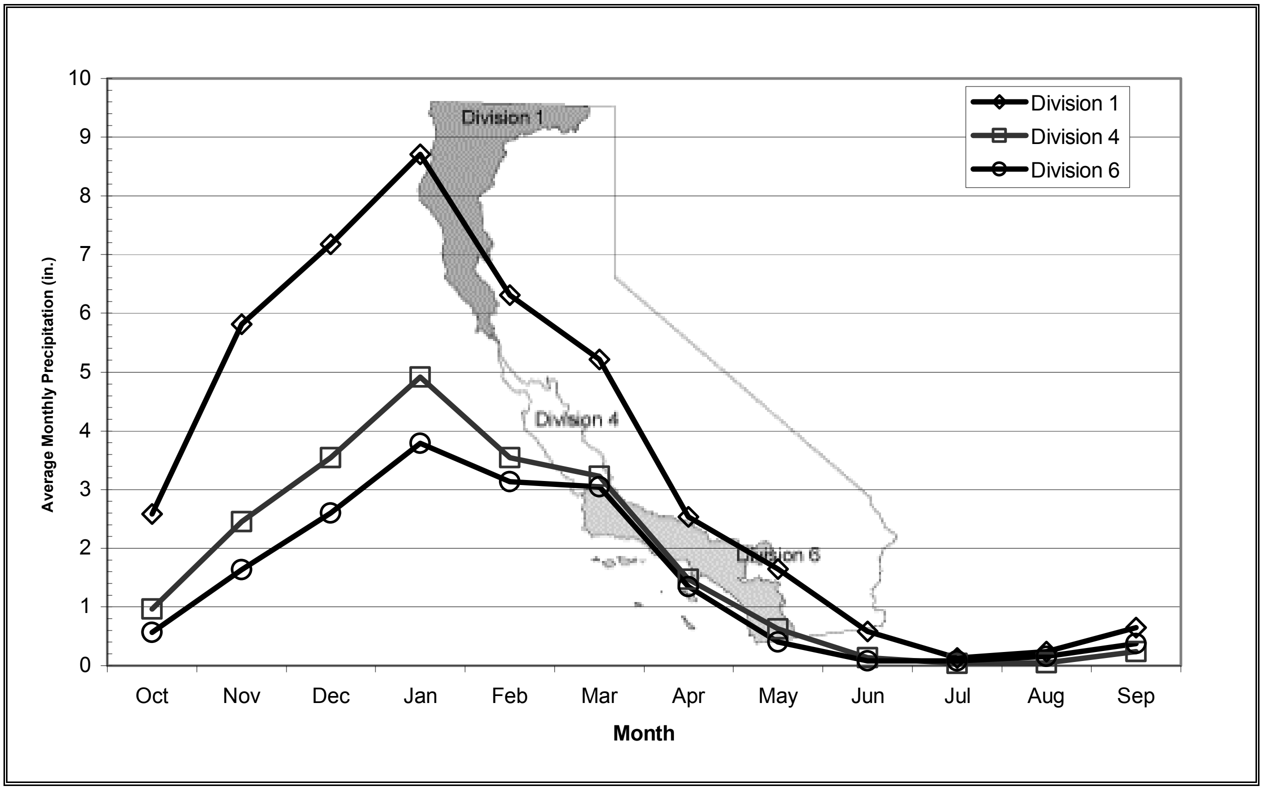

Figure 7.1 Regional comparison of average monthly precipitation, water years 1886 to 2000

*(*Data Source: National Climate Data Center, 2001*)*

This regional imbalance in precipitation results in a regional gradient in average daily water discharge. Figure 7.2 shows the average monthly discharge for three minimally-impeded rivers draining similar size basins (100 to 150 square miles), for which less than 5% of the basin areas are controlled by dams. Peak discharges tend to occur in all three regions during January, February, and March when soils have reached saturation and additional rainfall is translated directly into run-off. This seasonal pattern of rainfall and streamflow depicted in Figures 7.1 and 7.2 is heightened by infrequent, exceptionally wet years when large floods flush enormous quantities of sediment out of coastal watersheds. A study of major rivers in Central and Southern California has shown that sediment discharge during flood years like 1969, 1983, or 1998 averages 27 times greater than during drier years (Inman and Jenkins, 1999). For example, in 1969 over 100 million tons of sediment were flushed out of the Santa Ynez mountains, more than the previous 25 years combined (Inman and Jenkins, 1999). Similarly, on the San Lorenzo River near Santa Cruz, CA, 63% of all the suspended sediment transported between 1936 and 1998 occurred over just 62 days (or less than 0.3% of the time over the 52 year period). These infrequent, severe floods occurring every 10 to 20 years are responsible for delivering the majority of beach material to the coast.

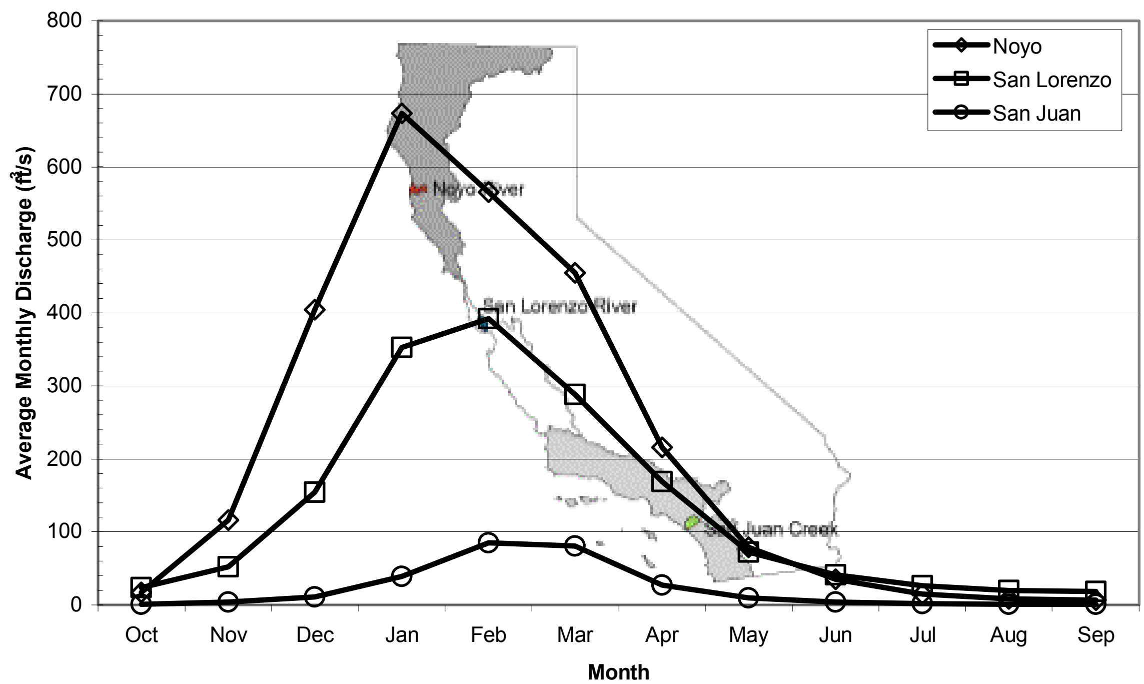

Figure 7.2 Regional comparison of average monthly water discharge, water years 1952 to 1999
*(*Data Source: USGS Water Resources Data, 1952-1999*)*

California's coastal rivers have exceptionally high sediment loads due to the steep topography, the geologically young and tectonically active terrain, and, in Central and Southern California, the relatively sparse vegetative cover. Sediment yield, the volume of sediment delivered per square mile of watershed, is typically very high in California relative to other major hydrographic regions of the United States. In fact, the Eel River in Northern California has the highest sediment yield of any river its size in the U.S. (Brown and Ritter, 1971) and discharges, on average, more sediment per year than any other river in the lower 48 states other than the Mississippi River (Meade and Parker, 1984).

7.1.2 Fluvial Sediment Input, by Watershed/Littoral Cell, from Major Waterways

In this study, all water discharge and sediment data published by the USGS through the 1999 water year (USGS Water Resources Data for California, 1999) has been compiled for the most seaward gaging stations for California's 34 gaged coastal streams to characterize the long-term fluvial delivery of beach material to the coast. Suspended sediment transport was estimated using a standard rating curve technique, where suspended sediment measurements are correlated with water discharge by a power function of the form $Q_s = a \cdot [Q_w]^b$, where Q_s is the daily suspended sediment flux (tons/day), Q_w is mean daily water discharge in ft^3/s, and a and b are constants. The daily estimated and measured suspended sediment fluxes were summed by water year. Suspended sediment grain size was found to have a very poor correlation with water discharge, presumably due to the variable supply of sediment on the bed through time. Therefore, the average value of the percent of sand in suspension was used to reduce annual suspended sediment delivery to just the volume of sand delivered in that year. Bedload rating curves were developed when data were available and grain size information from the bed surface was used to assess the sand and gravel fraction of the bedload. The annual suspended sand and bed sand and gravel fluxes were summed together to determine the total annual flux of beach material (Q_L). The average annual sand and gravel discharge (Q_L) was calculated over the period of record to reflect the long-term average sand and gravel discharge for each river. When bedload information was not available, bedload was assumed to be 10% of the annual suspended sediment flux and 100% sand or coarser, an estimate often used by researchers in lieu of direct measurements (Brownlie and Taylor, 1981; Hadley et al., 1985; Inman and Jenkins, 1999). Errors in estimating suspended sediment flux arise from measurement errors of suspended sediment in the field and statistical errors in rating curve calculations. Overall uncertainty for suspended sediment discharge estimates has been estimated at a maximum of ±35% (Inman and Jenkins, 1999). In a few cases, no suspended sediment data were available, so long-term sediment flux was based on reservoir sediment accumulation rates within the basin or sediment yields of adjacent watersheds. For example, accumulation rates in three reservoirs in the Santa Ynez basin indicate an average sand and gravel yield of 440 yd^3/mi^2-yr; this average yield was applied to the Santa Ynez watershed area not affected by dams to estimate the long-term average annual sand and gravel yield. For 5 rivers that had neither suspended sediment nor sediment accumulation data, Q_L was estimated by applying the average annual sand and gravel yield of adjacent watersheds with sediment data to the basin area not affected by dams. Previously-published estimates of sand and gravel discharge were used for 5 Southern California rivers.

Table 7.1 summarizes the long-term average annual sand and gravel discharge (Q_L) from all major gaged streams in California. The sand discharge includes all sand-sized material (0.062

to 2.0 mm), but sediment budget studies along the California coast have found that much of the fine sand (between 0.062 and 0.125 mm) is too small to remain on the beach (Ritter, 1972; Best and Griggs, 1991). Therefore, the sand flux estimates provided in Table 7.1 should be considered maximum estimates of beach quality material supplied from coastal streams. It is worthwhile to note that the sand flux in any given year does not necessarily reflect the average annual sand flux reported in Table 7.1. Sediment delivery is a highly episodic process in which extremely wet years deliver most of the sediment to the coast as discussed in the previous section. Thus, the average annual flux includes both the occasional high discharge years and the more frequent moderate and low flow years. This concept is illustrated for two rivers with similar basin sizes and less than 5% of their drainage areas impacted by dams, the San Lorenzo River and San Juan Creek (Figure 7.3). Southern California rivers, like San Juan Creek, appear to experience more extreme episodicity in sediment delivery than rivers in Central and Northern California.

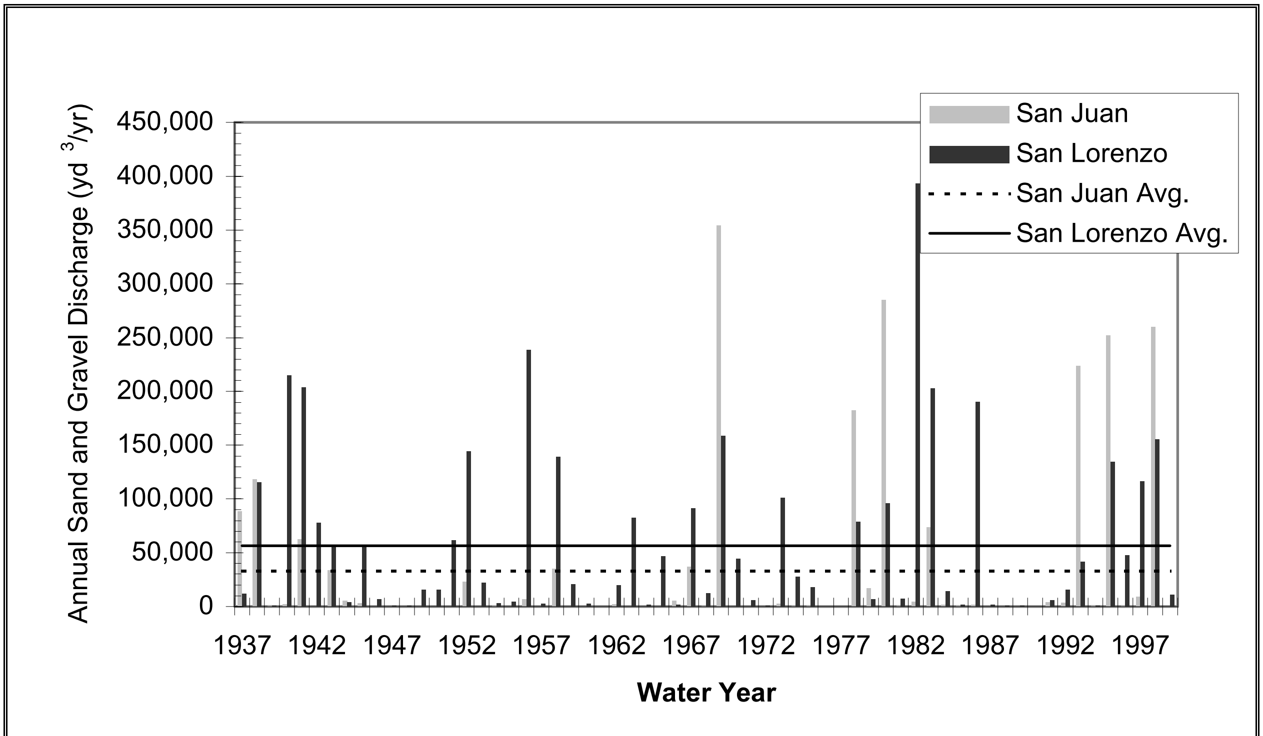

Figure 7.3 Comparison of San Lorenzo River and San Juan Creek annual sediment delivery, water years 1937 to 1999

Table 7.1 Summary of Average Annual Sediment Discharge for Major California Rivers

(Source: Data developed in this study unless noted otherwise)

Major Rivers	Average Annual Flux Q_L (yd^3/yr)	Period (Water Yr)	Area above gage (mi^2)	Sand and Gravel Yield (yd^3/mi^2-yr)
Smith River [a]	178,503	1932 - 1999	614	291
Klamath River [a]	1,668,122	11-26, 55-96, 98-99	12,100	138
Redwood Creek [a]	335,205	1954 - 1999	277	1,210
Little River [b]	53,208	NA	41	1,314
Mad River [a]	687,340	1951 - 1999	485	1,417
Eel River [a]	3,753,107	1917 - 1999	3,113	1,206
Mattole River [b]	232,295	NA	245	947
Noyo River [b]	100,417	NA	106	947
Navarro River [a]	208,868	1951 - 1999	303	689
Russian River [a]	183,106	1940 - 1999	1,338	137
Pescadero Creek [a]	9,294	1952 - 99	46	202
San Lorenzo River [a]	56,359	1937 - 99	106	532
Pajaro River [a]	60,475	1940 - 99	1,186	51
Salinas River [a]	488,734	1930 - 99	4,156	118
Carmel River [a]	32,265	1963 - 99	246	131
Arroyo Grande	37,325	1940 - 86	102	366
Santa Maria River [a]	260,764	1941 - 87	1,741	150
San Antonio Creek [b]	60,290	NA	135	447
Santa Ynez River [c]	347,078	1920-99	789	440
Ventura River [a]	102,252	1930 - 99	188	544
Santa Clara River [a]	1,193,102	1928 - 32, 1950 - 99	1,594	748
Calleguas Creek [a]	64,932	1969 - 99	243	267
Malibu Creek [1]	34,007	1960 - 99	100	238
Ballona Creek [2]	2,890	1944 - 95	130	22
Los Angeles River [a]	77,187	1930 - 83, 1989 - 92	827	93
San Gabriel River [b]	59,246	NA	709	84
Santa Ana River [a]	125,316	1924 - 99	1,700	74
San Diego Creek [a]	16,208	1950 - 85	42	388
San Juan Creek [a]	29,874	1929 - 99	109	274
Santa Margarita River [a]	39,877	1931 - 98	723	55
San Luis Rey River [a]	39,907	1947 - 97	557	72
San Dieguito River [3]	12,507	1919 - 78	338	37
San Diego River [3]	6,581	1913 - 75	377	17
Tijuana River [3]	42,100	1937 - 75	1,695	25

[a] Q_L derived from measured suspended sediment data, bedload data, and rating curves

[b] Q_L based on watershed area and sediment yield of adjacent basins

[c] Q_L based on watershed area and sediment accumulation data

[1] Knur, 2001

[2] Inman & Jenkins, 1999

[3] Brownlie and Taylor, 1981

7.2 Dams

Central and Southern California are the sites of the state's main urban centers: the San Francisco Bay area, Los Angeles, and San Diego. Major agricultural regions—San Joaquin Valley, Salinas Valley, and Imperial Valley—also are located in this region. Today, 56% of California's 34.3 million residents live in the coastal counties from San Francisco to San Diego (California Department of Finance, 2000), but the majority of the state's precipitation—75%— falls north of San Francisco (California Rivers Assessment, 1992). To meet the urban and agricultural water demands, California has developed a complex network of dams, reservoirs, and aqueducts capable of storing 60% of the state's annual runoff and transporting it from water-rich Northern California to water-poor Central and Southern California (California Rivers Assessment, 1992).

To support California's exponential population growth over the twentieth century, over 1,400 large dams have been constructed across the state for a number of purposes, including water storage, irrigation, flood control, recreation, and hydroelectric power (see Figure 7.4). There are undoubtedly a much larger number of small dams and obstructions that inhibit sediment transport in California streams; however, this study only addresses dams that fall under the jurisdiction of the California Department of Water Resources Division of Safety of Dams (Division of Safety of Dams, 1998), which include dams that are either at least 25 feet high or impound 50 or more acre-feet of water.

7.2.1 Inventory of jurisdictional dams and reservoirs

Since the construction of the first major dam in California in 1866, an average of 3.5 dams per year have been built, for a total of 480 dams in the study area. An additional 60 dams in Oregon and Mexico affect flows in California's coastal watersheds. The study area includes all watershed area that drains directly to the Pacific Ocean (Figure 7.4), excluding areas draining to the San Francisco Bay. The primary purposes of dams in this area are water supply (33%), irrigation (21%), flood control (19%), and recreation (11%) (EPA, 1998). The majority of coastal dams are owned and operated by local governments and water districts (52%), followed by private companies or individuals (31%), and federal (13%) and state agencies (4%) (Division of Safety of Dams, 1998).

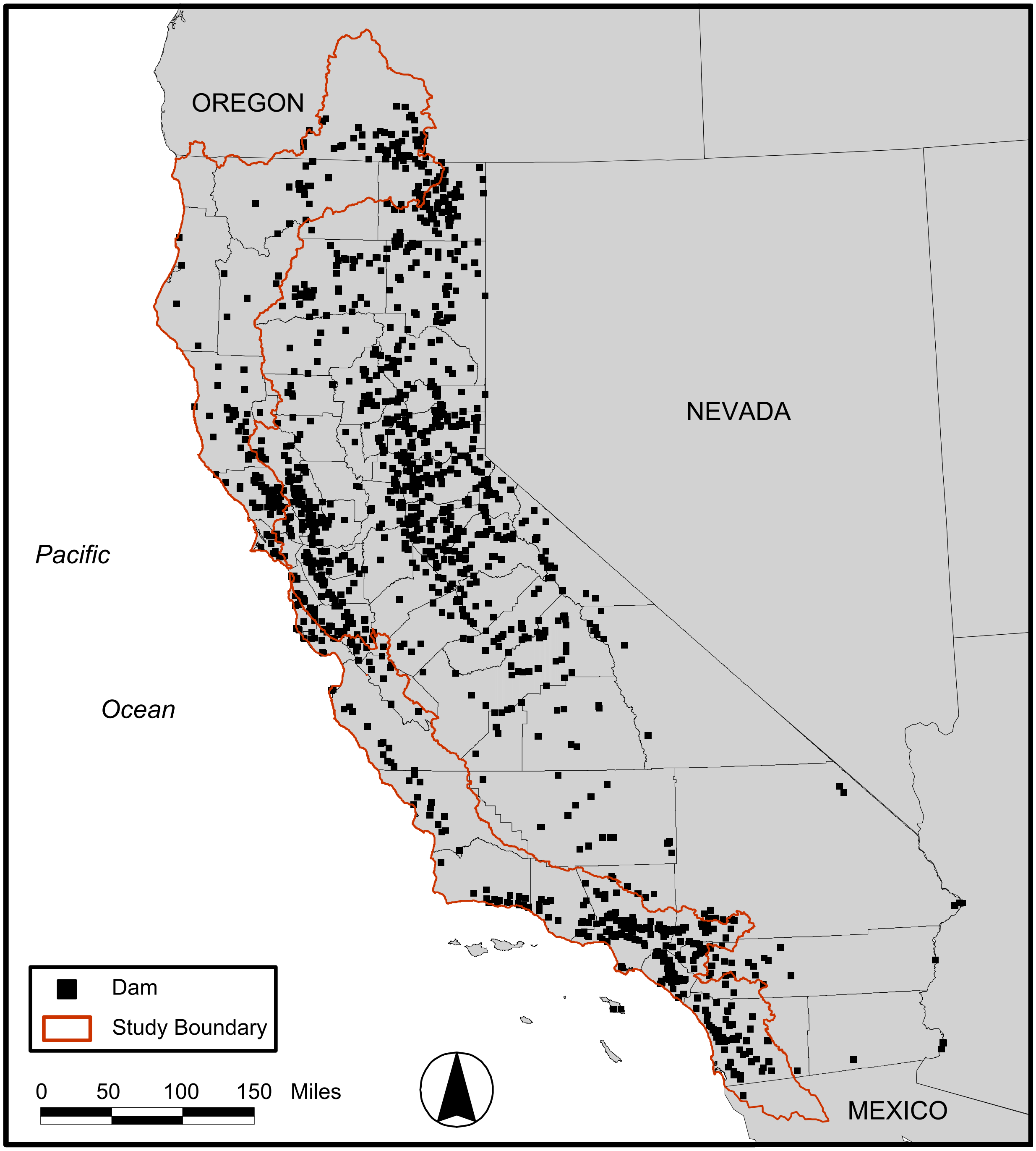

Figure 7.4 Distribution of Large Dams in California

(Data Source: Division of Safety of Dams, 1998)

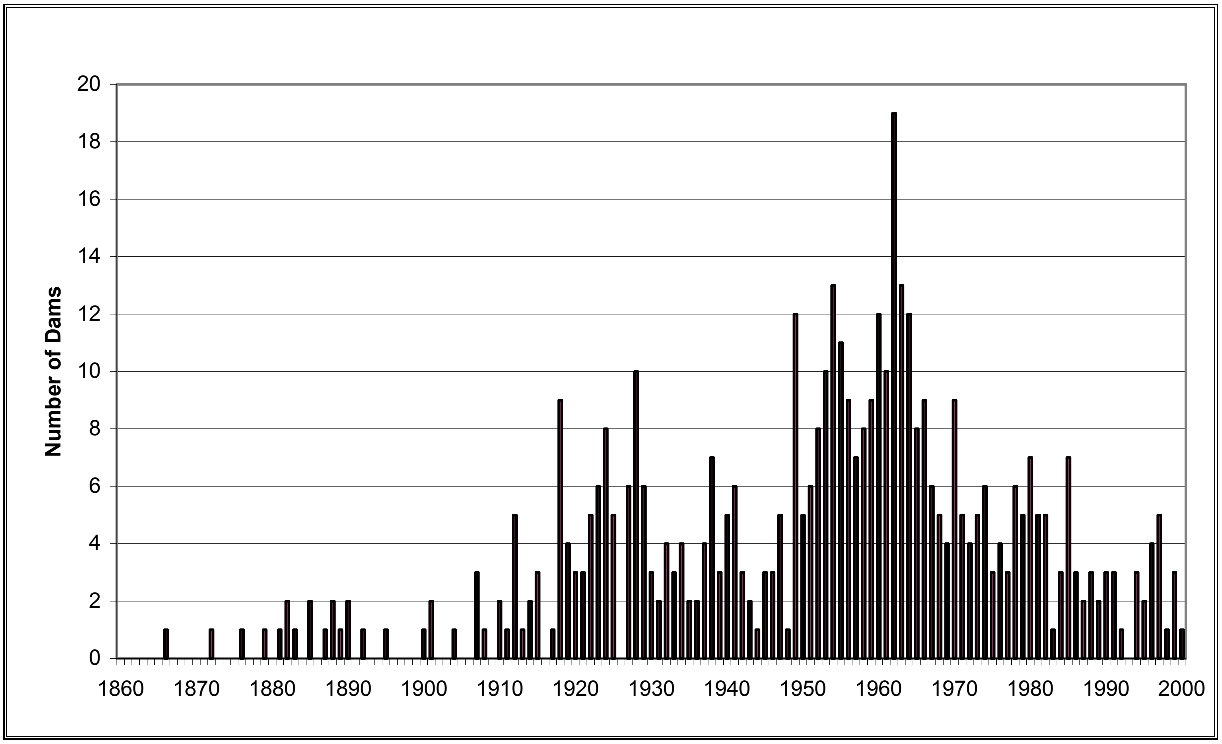

Figure 7.5 Number of dams built each year in California coastal watersheds, 1860 to 2000
(Data Source: Division of Safety of Dams, 1998)

Dam construction trends can be assessed by either the number of individual dams built in a year or by the cumulative water storage or flood control capacity. By both accounts, maximum activity occurred between 1945 and 1977, when 61% of the water storage capacity and 50% of the total number of dams in the study area were built (Figures 7.5 and 7.6). This time period coincides with a prolonged period of below-average rainfall in Southern California (where 58% of the dams in the study area reside): below-average precipitation fell in 27 of the 33 years (82%; National Climate Data Center, 2001). In addition, this time period is marked by two decades of exceptionally high rates of population growth for the 20th century (California Department of Finance, 2000). Since 1978, California has experienced 3 strong El Niño events and 14 of 22 years (65%; National Climate Data Center, 2001) with above-average precipitation. Despite the relatively wet climatic conditions dominant since 1978, 20% of the coastal water storage capacity has been built since 1990, including the largest dam in the study area, the Diamond Valley Lake (formerly called Eastside Reservoir), designed to store 800,000 acre-ft of water (Division of Safety of Dams, 1998). The total water storage capacity of the coastal dams represents only 12% of the total statewide water storage capacity (42.6 million acre-ft; California Rivers Assessment, 1992).

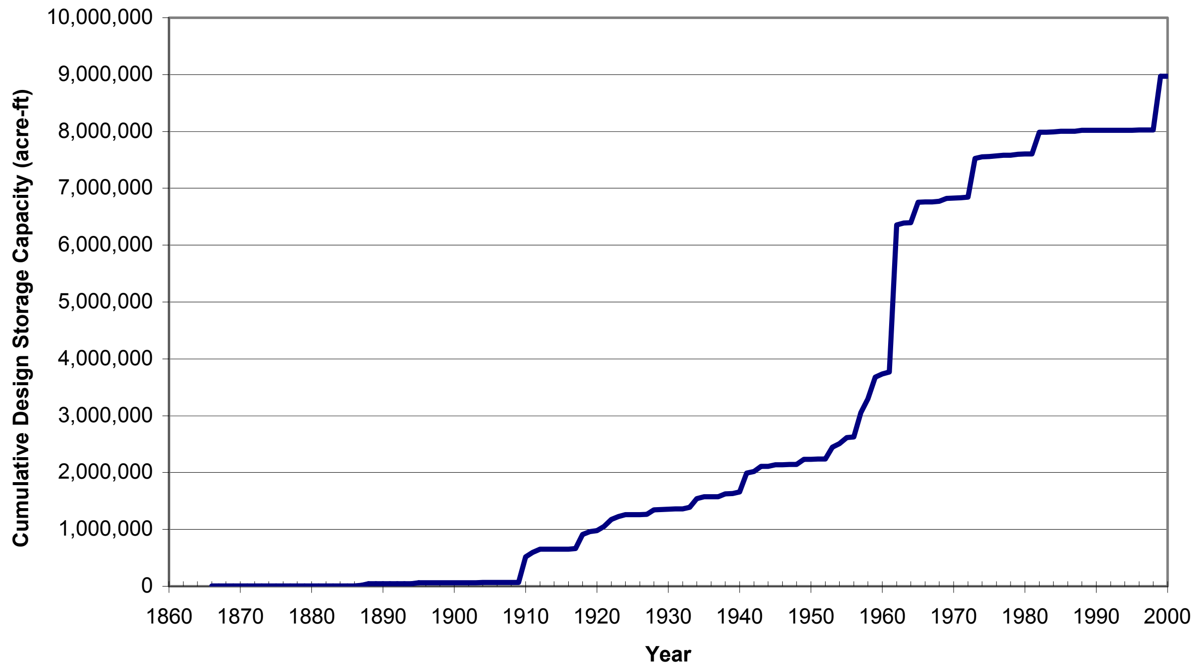

Figure 7.6 California coastal dam capacity through time, 1860 to 2000
(Data Source: Division of Safety of Dams, 1998)

California's water engineering system has drastically altered the natural behavior of most of the state's major rivers and streams. Dams change the magnitude and timing of river flows, trap sediment, alter river temperatures, and impede or completely obstruct the movement of fish upstream of the dam, contributing to the decline of Pacific salmon and steelhead trout populations in California. By trapping sediment and altering the hydrology of streams, dams can alter water discharges, sediment load, channel incision rates, and channel morphology below the dam (Williams and Wolman, 1984).

7.2.2 Impact of Dams on Sediment Discharge

Dams can reduce sediment supply to beaches in two ways: (1) by trapping sediment behind the dams and (2) by reducing peak river flows that transport sand below the dam. Upstream, dams create a reservoir of still water in which all bedload is trapped and all but the finest suspended sediment settles to the reservoir bottom. Brune (1953) demonstrated that the amount of suspended sediment impounded, or the trapping efficiency of dams, depends on the ratio of water inflow to reservoir capacity. For California's large reservoirs, the trapping efficiency is nearly 100% (Kondolf and Matthews, 1991). Channel degradation, bank erosion, and bed-coarsening have been documented immediately downstream of dams and have been attributed to the "hungry waters" effect—an increase in stream power resulting from reduced sediment loads

(Williams and Wolman, 1984; Kondolf and Matthews, 1991). More importantly for coastal sediment delivery, however, dams restrict the volume and speed of the water traveling in the river channel, diminishing the competence and capacity of the river to carry sediment. Researchers have also shown that dams on the main stems of rivers may disrupt the synchronous high flows on the main stem and tributaries with important implications for sediment transport (Topping et al., 2000).

As early as 1938, coastal researchers recognized the implications of the proliferation of dams in California's coastal watersheds on beach sand supply (Grant, 1938). Not until the latter half of the century, however, did researchers attempt to quantify the volume of sediment impounded by dams (Norris, 1963; DNOD, 1977; Brownlie and Taylor, 1981; Griggs 1987; Flick 1993). Brownlie and Taylor (1981) completed the most rigorous of these studies, estimating average annual sand reductions for watersheds in Southern California through the 1978 water year. Now, there are 21 additional years of discharge and sediment data with which to better characterize the degree to which dams have reduced sand supply to the coast.

In contrast to studies on other major rivers like the Colorado (Topping et al., 2000), the Missouri (Williams and Wolman, 1984), and the Green (Andrews, 1986), there are no published pre-dam sediment data for USGS gaging stations on regulated coastal streams in California to directly compare to post-dam sediment loads. When pre- and post-dam sediment transport data are available for a river, the reduction in sediment transported is evident (Figure 7.7).

For many streams in California, pre- and post-dam streamflow data are available, but because of the high degree of annual variability in streamflow it is difficult to distinguish between natural climate variability and the effects of dams in a statistically rigorous manner. Therefore, to quantify the role of dams in reducing sediment supply to the coast, we used two approaches in conducting this study: (1) the difference between daily water inflow and release rates to estimate natural flows and sediment transport at coastal gaging stations, using the methodology of Brownlie and Taylor (1981); or (2) using reservoir sediment accumulation data to assess the sediment yield of impounded watershed areas and the resulting reduction in sediment yield for the entire basin. For several streams in Southern California, estimates of sediment reduction by previous researchers were used, due either to a lack of new data (Santa Margarita, San Dieguito, San Diego, and Tijuana rivers) or to the complexity of the watersheds (Los Angeles, San Gabriel, and Santa Ana rivers). In addition to the sediment transport investigation, all major dams, streams, topography, and watersheds were entered in a geographic information system (GIS) to generate accurate maps and to permit spatial analysis. Watershed areas controlled by dams were delineated using 100-meter digital elevation models (DEMs) to illustrate the broad geographic influence of coastal dams.

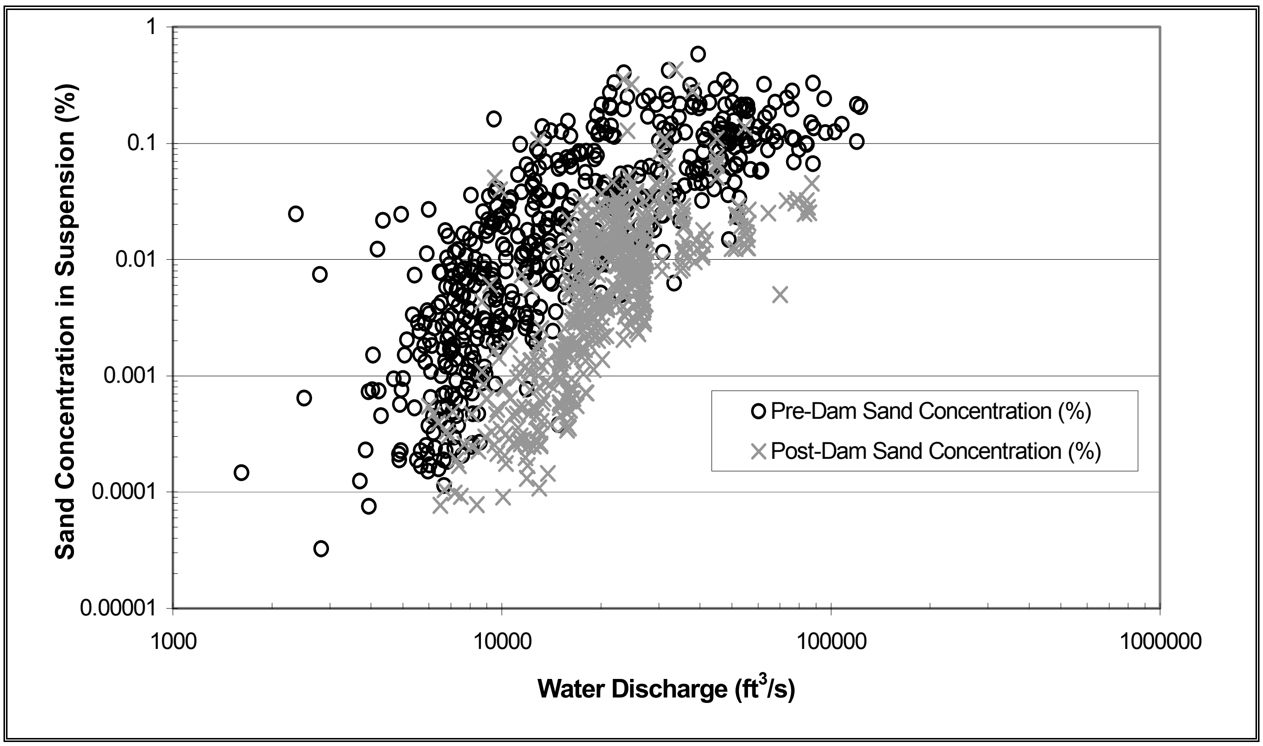

Figure 7.7 Comparison of measured sediment loads on the Colorado River before and after construction of Glen Canyon Dam

(Data provided by D. Rubin, USGS; measurements were made 90 miles downstream of the dam)

Dams affect more than 38% of California's coastal watershed area (Figure 7.8), impacting important habitat and sand contributions from over 16,000 mi^2 (an area roughly equivalent to the combined area of Massachusetts and New Hampshire).

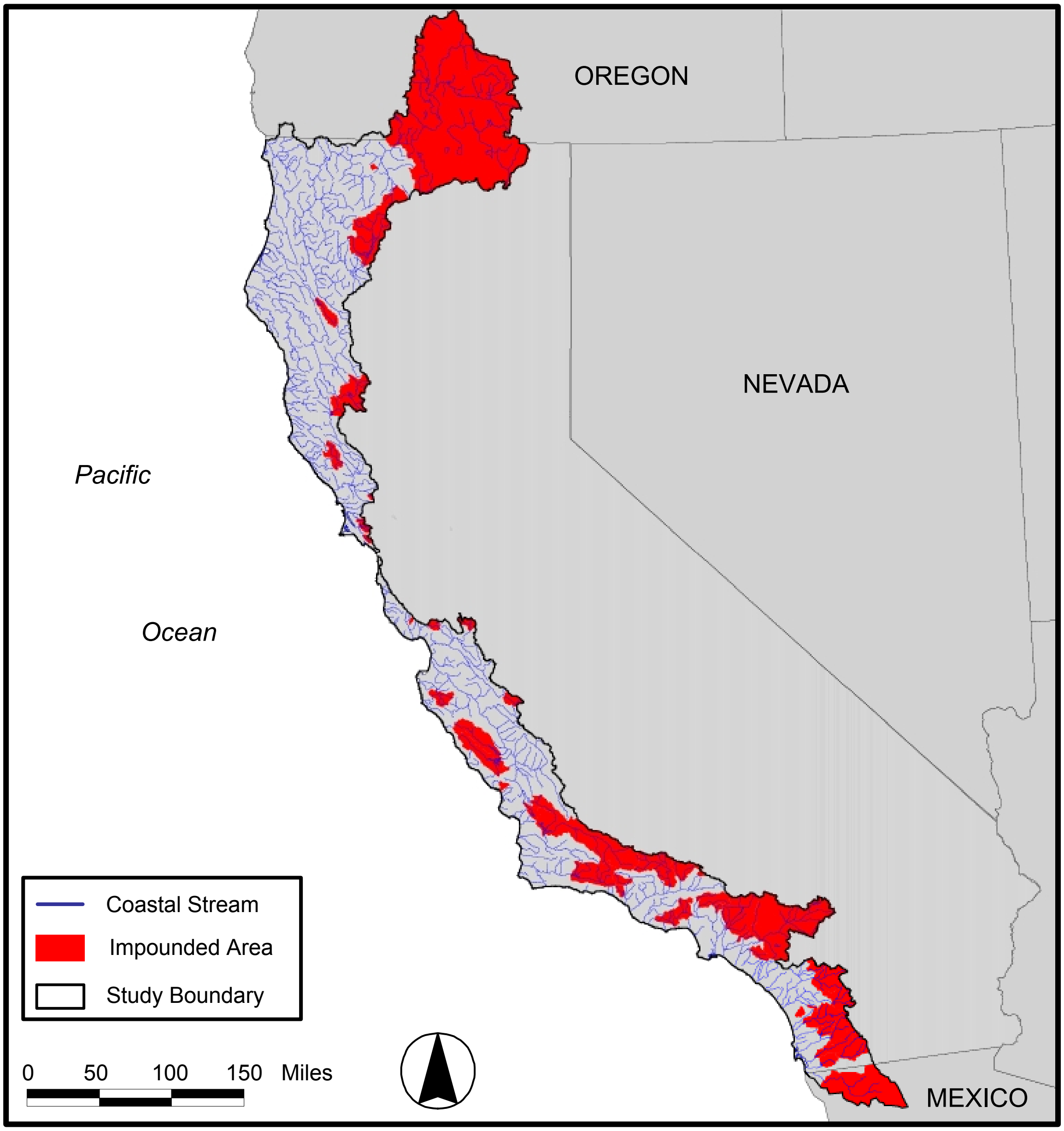

Figure 7.8 Major coastal watershed areas affected by dams

Table 7.2 summarizes the watershed areas controlled by dams, present average annual sediment yield for major coastal rivers, and the current level of reduction in sand and gravel supply due to dams.

Table 7.2 Summary of Sediment Reduction due to Dams by Littoral Cell

(Source: Data developed in this study unless noted otherwise)

Littoral Cell Name	Major Rivers	Percent Controlled	Present Avg. Annual Q_L Flux (yd^3/yr)	Present % Q_L Reduction
Smith River	Smith River	0	178,503	**0**
Klamath River	Klamath River	46	1,668,122	37
	Redwood Creek	0	335,205	0
	Total	45	2,003,327	**33**
Eel River	Little River	0	53,208	0
	Mad River	24	687,340	9
	Eel River	8	3,753,105	1
	Total	10	4,493,654	**2**
Mattole River	Mattole River	0	232,295	**0**
Ten Mile & Navarro River	Noyo River	1	100,417	0
	Navarro River	0	208,868	0
	Total	0	309,285	**0**
Russian River	Russian River	19	183,106	**17**
Santa Cruz	San Gregorio-Pescadero[1]	5	25,119	0
	San Lorenzo-Soquel	5	104,124	2
	Pajaro	15	60,475	6
	Total	12	189,718	**3**
Southern Monterey Bay	Salinas	19	488,734	**33**
Carmel River	Carmel	40	32,265	**59**
Pt. Sur & Morro Bay	Little & Big Sur Rivers[2]	3	179,388	**0**
Santa Maria	Arroyo Grande	46	37,325	67
	Santa Maria River	61	260,763	68
	San Antonio Creek	0	60,290	0
	Total	54	358,378	**64**
Santa Ynez	Santa Ynez River	47	347,078	**51**
Santa Barbara	Santa Ynez Mtn streams[3]	2	195,109	0
	Ventura River	37	102,252	53
	Santa Clara River	37	1,193,102	27
	Calleguas Creek	6	64,932	0
	Total	27	1,555,395	**26**
Santa Monica	Malibu Creek[4]	62	23,805	55
	Santa Monica Mtn streams[4]	0	43,332	0
	Ballona Creek[3]	7	2,890	0
	Total	23	70,027	**26**
San Pedro	LA River	54	77,187	67[5]
	San Gabriel	85	59,246	67[5]
	Santa Ana River	93	125,315	67[5]
	San Diego Creek	8	16,208	0
	Total	79	277,957	**66**

Oceanside	San Juan-Aliso Creek[2]	5	39,875	0
	Santa Margarita River	51	39,877	31[5]
	San Luis Rey River	39	39,907	69
	San Dieguito River[5]	89	12,508	79
	Total	44	132,166	**54**
Mission Bay	San Diego River[5]	63	6,581	**91**
Silver Strand	Tijuana River[5]	64	42,100	**49**
Total		38	11,079,954	**26**

[1] San Gregorio Creek and small Santa Cruz mountain stream inputs from Best and Griggs, 1991

[2] Big Sur River, Little Sur River, and Aliso Creek estimates from DNOD, 1977

[3] Inman & Jenkins, 1999

[4] Knur, 2001

[5] Brownlie and Taylor, 1981

The cumulative effect of these coastal dams has been to reduce the average annual sediment supply by more than 25% to California's 20 major littoral cells. Half of California's littoral cells currently receive less than two thirds of historical fluvial sediment supplies. In Southern California, (Point Conception to San Diego), sediment supply to the coast has been reduced by over 50% to half of the littoral cells; in the other half, reductions range from 26% to 49%. The greatest decrease in fluvial sediment delivery has occurred in the areas with the greatest demand for recreational beaches.

7.2.3 Sediment Impounded in Selected Reservoirs

Some of the effects of sediment impoundment by dams in the coastal watersheds of Southern California have been documented or predicted in studies by Brownlie and Taylor (1981), Griggs (1987), Inman (1989), Flick (1993), Inman and Jenkins (1999), and Barron (2001). The previous section predicted transport rates downstream of dams in coastal watersheds in California. These predictions are based on stream discharge records. To complement those model estimates, we have collected sedimentation data for several of those reservoirs based upon empirical data.

Sedimentation rate data were obtained for fourteen reservoirs/dams in Central and Southern California (Figure 7.9). The dams were selected based upon the size of the undammed drainage basin that they control (at least thirty square miles), proximity to the coast (less than thirty miles from the ocean), and the availability of data. The dams included are Los Padres and San Clemente Dams in Monterey County; Bradbury (Lake Cachuma) and Twitchell Dams in Santa Barbara County; Matilija and Santa Felicia (Lake Piru) Dams in Ventura County; Big Tujunga, Devil's Gate, Hansen, Puddingstone, San Gabriel, Santa Fe, and Sepulveda Dams in Los Angeles County, and Prado Dam in Riverside County.

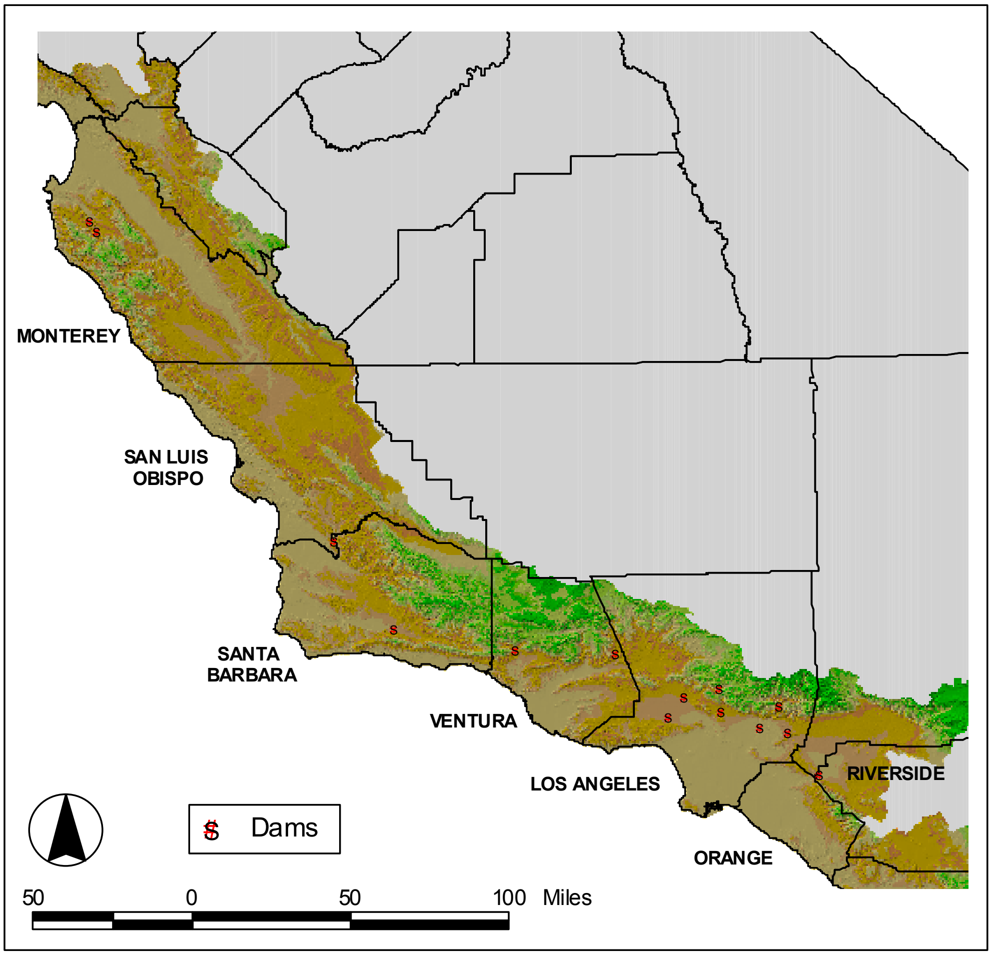

Figure 7.9 Distribution of the fourteen dams for which sedimentation rate data are presented
(Individual dams are identified in Appendix A)

The dams listed above reduce sediment delivery to the coast substantially. Summing the longest-term sedimentation rates for each of the fourteen dams (Table 7.3), it appears that the collective impact has been a total impoundment of about 273 million cubic yards of sediment, or an average impoundment rate of 5,990,000 cubic yards of sediment per year. Some of this sediment is in the size range commonly found on California beaches. However, most of the sediment is too fine or too coarse to be considered beach quality. For example, at Twitchell Reservoir, almost all of the 1,730,000 cubic yards of sediment trapped per year is too fine to remain on beaches. Taylor (1981) reports that sediments trapped in Lake Piru, behind the Santa Felicia dam in Ventura County, have a sand content (mean grain diameter larger than 0.062 mm and smaller than 2.00 mm) of about 20%. Taylor also suggests that the typical sand content of sediments trapped in the reservoirs in Santa Barbara and Ventura counties is about 20% (based mainly on the Lake Piru data), and, for the reservoirs in southern Los Angeles and Riverside Counties, sand content is about 50%. The contribution of the Monterey County reservoirs to the total impoundment rate is relatively small. For these reservoirs, we assumed 20% sand content as a conservative estimate. Applying these sand content data to the calculated impoundment rate for these reservoirs of 5,990,000 cubic yards per year, we obtain an estimated sand impoundment rate of about 1,330,000 cubic yards per year. Based on this analysis, about 90% of this sand (1,160,000 cubic yards per year) is trapped behind three structures: Hansen Dam and San Gabriel Dam in Los Angeles County, and Prado Dam in Riverside County.

Table 7.3 Sedimentation Rates in Selected Reservoirs

Dam	County	Watershed	Purpose*	Year Built	Period of Record	Sedimentation Rate (yd^3/yr)
Los Padres	Monterey	Carmel	water sup	1949	1949-2000	30,000
San Clemente	Monterey	Carmel	water sup	1921	1921-1996	30,000
Bradbury	Santa Barbara	Santa Ynez	water sup	1953	1953-2000	580,000
Twitchell	Santa Barbara	Santa Maria	water sup, flood con	1958	1958-1999	1,730,000
Matilija	Ventura	Ventura	water sup	1947	1947-1999	200,000
Santa Felicia	Ventura	Santa Clara	water sup, rec	1955	1955-1996	500,000
Big Tujunga	Los Angeles	Los Angeles	water sup, flood con	1931	1931-1982	230,000
Devil's Gate	Los Angeles	Los Angeles	water sup, flood con	1919	1919-1982	120,000
Hansen	Los Angeles	Los Angeles	flood con	1940	1940-1983	420,000
Puddingstone	Los Angeles	San Gabriel	flood con, rec	1925	1925-1980	50,000
San Gabriel	Los Angeles	San Gabriel	water sup, flood con	1932	1937-1983	77,000
Santa Fe	Los Angeles	San Gabriel	water sup, flood con	1943	1943-1982	200,000
Sepulveda	Los Angeles	Los Angeles	flood con	1941	1941-1980	trivial
Prado	Riverside	Santa Ana	flood con, rec	1941	1941-1979	1,130,000

* water sup = water supply; rec = recreation; flood con = flood control

From a sediment budget perspective, coastal dams can disrupt the long-term balance of sediment gains and losses to the coast, tipping the balance toward a long-term net loss of sand (Figure 7.10). Since fluvial sediment deliveries account for 70 to 90% of beach sand in California (Bowen and Inman, 1966; Best and Griggs, 1991), beaches can be expected to diminish in size if dams significantly reduce sediment supplies, such as in the 10 littoral cells that have experienced sediment reductions by 33% or more. To date, there have been no comprehensive studies to determine if long-term beach loss is occurring in California. However, there are many well-documented beach erosion "hot spots," including the Ventura County coastline, Malibu and the northern San Diego County coastline, that have been attributed qualitatively to dams by a number of sources (e. g. Noble Consultants, 1989; Capelli, 1999).

Artificial nourishment in Southern California kept pace with sediment losses from dam construction during the twentieth century (Flick, 1993). As large harbors were excavated and other large construction projects were undertaken (e.g. San Onofre Generating Station) along

Southern California between 1940 and 1960, over 130 million cubic yards of sand were placed on the region's beaches (Flick, 1993). However, by the late 1960's, harbor construction and the associated nourishment activities were curtailed. In some areas, the nourishment activities built beaches that were larger than previously maintained by the natural system. In other areas, the nourishment simply offset sand losses caused by dams. In short, beach nourishment has been a short-lived engineering solution to a long-term engineering problem: sediment impoundment by dams.

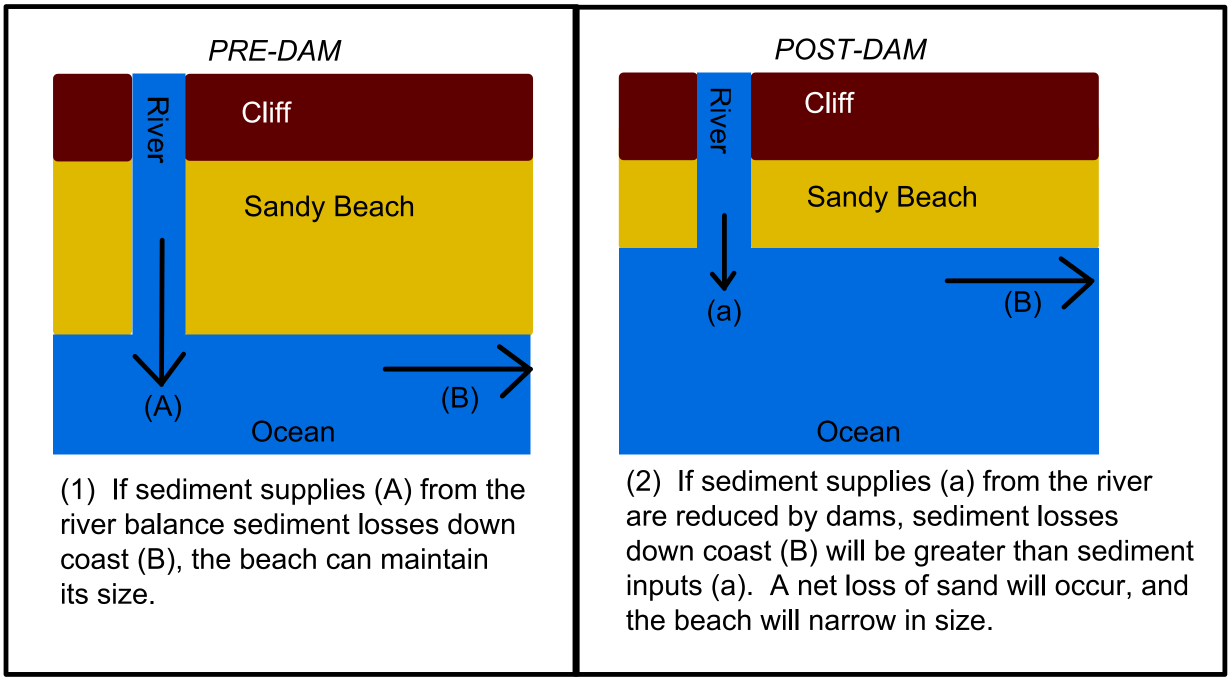

Figure 7.10 Potential impact of dams on long-term beach size

7.3 Debris Basins

7.3.1 Impact of Debris Basins on Sediment Supply

Debris basins are small catchments designed to trap coarse sediments while allowing the passage of water and fine sediments. Of principal concern in the location and design of these basins is the reduction of hazard posed by debris flows. A debris flow (commonly referred to by non-specialists as a "mud flow") is a form of slope failure where flood waters entrain large concentrations of unconsolidated, coarse sediments and flush them downstream at velocities that may approach 100 miles per hour. The sediment load in debris flows increases their density well above that of clear water, and thereby increases their potential to produce damage. Debris basins reduce the debris flow danger to the extent that they are able to trap the material being transported.

Debris basins are created by the construction of dams across intermittent or ephemeral stream channels, and they have typical capacities between 1,000 and 500,000 cubic yards. Plate 7.1 shows part of the La Tuna Canyon debris basin, located in Los Angeles County. The dam is earthen, with a concrete spillway to accommodate large discharge events. The tower at the base of the spillway is a drain that allows water and fine sediments to pass through its holes and continue downstream past the dam. In many debris basins, these vertical drains display markers that serve as indicators of basin capacity vis-à-vis the surface elevation of sediment deposits. Such markers are typically used to indicate when a basin should have its sediment deposits removed. Sediment removal is routinely required in order to maintain a basin's protective function.

Plate 7.1 The La Tuna Canyon debris basin (Photograph courtesy of K. Barron)

Debris basins have been used extensively in Southern California to reduce the magnitude of debris flows that threaten life and property in developed areas. Indeed, the majority of the debris basins in California have been built around the perimeter of the Los Angeles Basin, in watersheds in the San Bernardino, San Gabriel, Santa Monica, and Santa Susana Mountains, and most of the remaining are found in neighboring Ventura and Orange Counties (Figure 7.11). These mountains frequently produce large debris flows that often have been quite damaging (Troxell and Peterson, 1937). There are three factors that influence the generation of debris flows in this region: climate, relief, and fire. First, the local climate is characterized by relatively long periods of below-average rainfall, punctuated by extreme rainfall events (discussed in the context of slope failure by Cooke 1984). The periods of low rainfall allow sediments produced by dry erosion (dry ravel) to accumulate on slopes and at the bottoms of gullies and ravines because there is insufficient runoff to wash them downslope. The intense rainfall events are capable of generating stream discharges that are able to quickly mobilize large volumes of the stored sediments.

Second, steep slopes also are important for producing debris flows. Such slopes enhance the transport of dry ravel into the beds of ravines, where it is then stored until flooding flushes it downstream. Other forms of slope failure (e.g., soil slips and landslides) also are common on steep slopes, and these processes contribute to the delivery of unconsolidated sediments into ravines. Such failures, often rainfall-induced, may be a direct triggering mechanism for the generation of a debris flow. Further, steep slopes are likely to produce substantial and rapid surface runoff for a given rainfall event. According to Campbell (1975), most debris flows in Southern California occur on slopes with angles between about 27^o and 45^o.

Third, the destruction of hill slope vegetation by wild fire increases the likelihood of debris flow generation. In the aftermath of a brush fire, there is an increase in sediment production and runoff from hill slopes in Southern California. Runoff is increased because the removal of vegetation reduces interception of precipitation and decreases transpiration. Further, infiltration rates in post-fire soils are usually slower than the antecedent condition. Sediment delivery is increased because of physical changes in soil characteristics and because the post-fire soil surface is exposed to direct erosion by rain splash and overland flow. These processes may increase sediment production from steep slopes by as much as two orders of magnitude (Wells, 1981). According to Ferrell (1959), erosion rates in the first year after a fire may be twenty times larger than those under normal conditions. Wells and Brown (1982) described such effects as persisting as long as a decade after a burn, although the impacts diminish throughout that period.

These three factors commonly are present in the mountains surrounding communities in Southern California. Debris flows have caused some of the most deadly natural disasters in Southern California history. The 1934 debris flow that devastated Montrose and adjacent communities may have killed nearly one hundred people (many of the victims were missing) – equivalent to the death toll from the Northridge earthquake in 1994 (e.g., Davis 1998). The threat of future catastrophic debris flows persists in California’s coastal mountain ranges, and the magnitude of threat is probably increasing because development continues in hazardous locations.

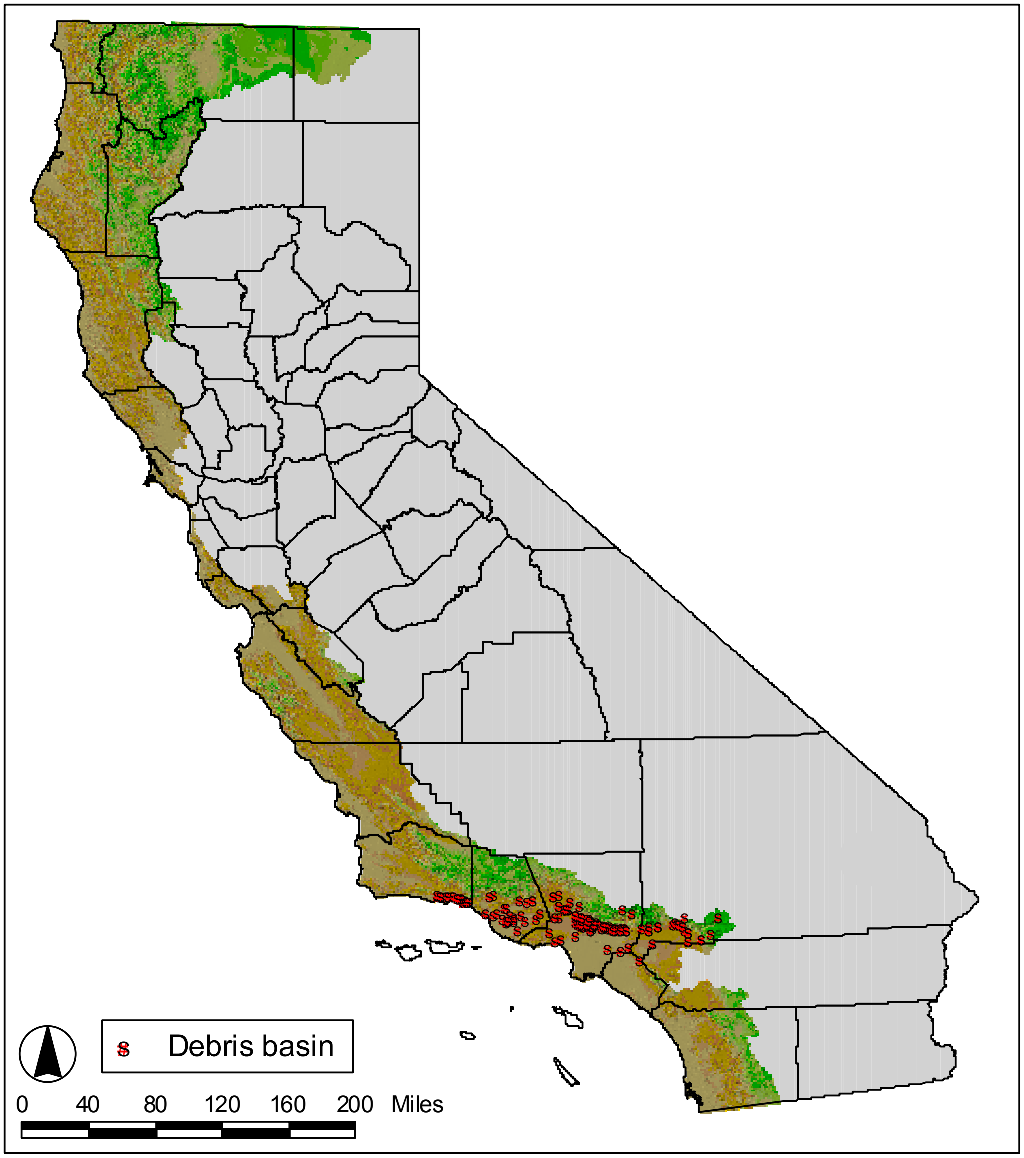

Figure 7.11 Distribution of debris basins in coastal watersheds in California.

7.3.2 Sediment Impoundment in Debris Basins

Debris basins are designed to trap sediments of sand size and larger, and they are generally quite successful in this endeavor. However, in accomplishing their design function, these basins also interrupt the movement of sediments from the mountains toward the coast. Sediment storage within debris basins degrades their utility. Therefore, agencies charged with basin maintenance have developed cleanout protocols. For example, the Los Angeles County Department of Public Works (LACDPW) has a protocol based upon loss of storage volume and fire history. According to Bohlander (personal communication cited in Barron 2001), a debris basin that is located in a watershed that has not been burned in the preceding four or five years will be allowed to lose about 25% of its capacity before normal maintenance cleanout is scheduled. In recently burned watersheds, cleanout occurs when 5% of the capacity is lost. In 2000, the drain (outlet) towers in LACDPW debris basins were marked with lines indicating the 5% and 25% capacity loss elevations to simplify estimation of debris volumes and to aid in recognition of basins where cleanout is appropriate. Most agencies keep records of cleanout projects that include volume of material removed. These data constitute a valuable record of sediment impoundment.

Kolker (1982) found that, as of 1978, a total of about 13,692,300 cubic yards of sediment had been removed from more than 100 debris basins in coastal watersheds in Ventura, Los Angeles, San Bernardino, Riverside, Orange, and San Diego Counties (although the latter two counties had few debris basins and no record of sediment removal). The number of debris basins included in that study cannot be determined because data for San Bernardino County were reported by watershed rather than by basin. Further, the length of time over which removal had occurred varied from county to county, and also depended on the age of individual debris basins. There is minimal information concerning the sediment grain size characteristics of these deposits. Therefore, the fraction of these deposits that lies within the sand size range is unknown. However, according to the work of Taylor (1981), it would not be unreasonable to assume that about 50% of these sediments are in the sand size range. Thus, through 1978, approximately 7,000,000 cubic yards of sand had been removed during the cumulative life spans of the debris basins in the counties listed above. It is presumed that little of this sand was returned to the drainage system, and therefore this removal ultimately represents a loss of sand from the coastal sediment budget.

7.3.3 Inventory of Debris Basins in Coastal Watersheds

We identified 194 debris basins in Santa Barbara, Ventura, Los Angeles, San Bernardino, and Riverside Counties (Figure 7.12). Data for these debris basins are presented in Appendix B. For Santa Barbara County, data collected through June 1998 were produced by the Santa Barbara County Flood Control & Water Conservation District and Water Agency. For Ventura County; the data source is the *Detention Dams & Debris Basins Manual*, prepared by the Hydrology Section of the Ventura County Flood Control District, as revised in June 1999. Data for Los Angeles County through the 1999-2000 storm season were provided through personal communication with Mr. Mike Bohlander, head of the Hydrologic Engineering Section of the Los Angeles County Flood Control District. Data for San Bernardino County were provided through personal communication with Mr. Tony Wimenta, Flood Control Zone Coordinator at the San Bernardino Department of Public Works. Data for Riverside County were provided through personal communication with Mr. Mike Biloki of the Riverside County Flood Control District.

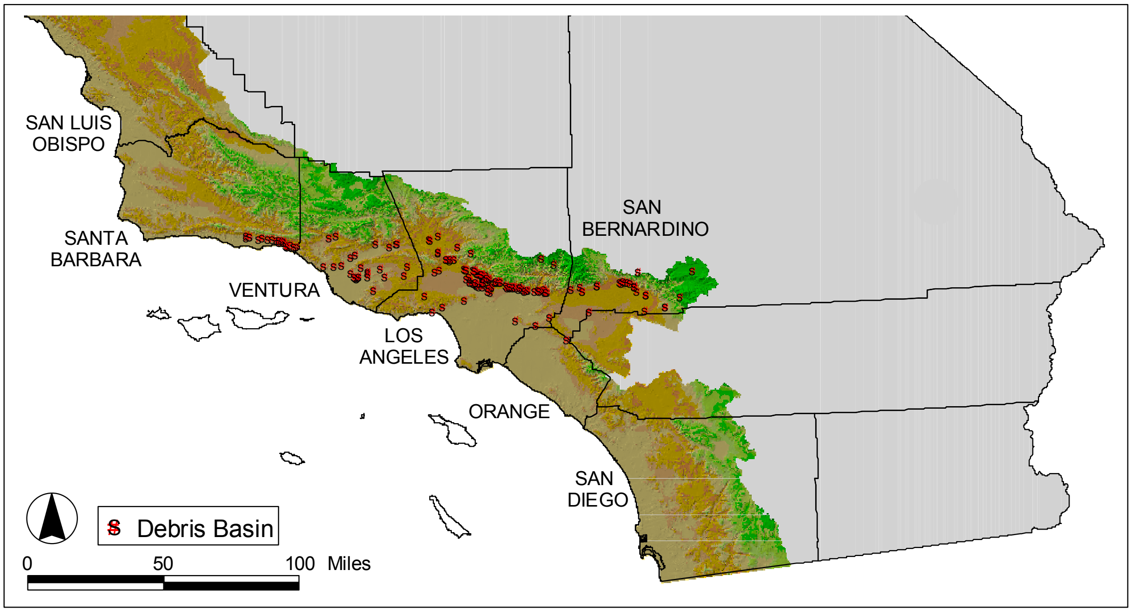

Figure 7.12 Distribution of debris basins in coastal watersheds in Southern California.

We were unable to locate quantitative data for purpose-built debris basins (that is, designed specifically to reduce debris flow speed and/or volume) in any other California counties. Additionally, we were not able to collect data for the many small structures and basins designed to retain small amounts of sediment (<1,000 cubic yards), usually to protect roads or prevent clogging of culverts or pipes. We were unable to obtain quantitative data on sediment accumulation and sediment removal for the 33 debris basins located in San Bernardino County. These basins are distant from the coast. For these reasons, the San Bernardino debris basins are not considered further in this report.

As of 2000, the 162 basins for which accumulation data were acquired (listed in the "Total Debris Deposited" column in Appendix B) trapped more than 18,000,000 cubic yards of debris over their cumulative periods of operation. About 17,600,000 cubic yards of debris have been removed in maintenance operations to preserve the capacity of the basins. Applying Taylor's (1981) estimate of 50% sand content to these deposits, these basins have trapped and had removed about 9,000,000 cubic yards of sand. Very little of the removed sediment is delivered directly to local beaches or returned to fluvial systems for eventual transport toward the coast (Barron, 2001).

Despite the relatively large net trapping effect of the debris basin population, the overall effect of individual structures is usually small. For example, 95 of the basins have each trapped less than 50,000 cubic yards of debris in total. Again using the Appendix B data, we can divide "Total Debris Deposited" by the age of a basin to determine average annual deposition rates. This process reveals that only 82 of the 162 basins have average sedimentation rates exceeding 1,000 cubic yards per year. Only 13 basins (listed in Table 7.4) have average sedimentation rates exceeding 10,000 cubic yards per year. If the assumption of 50% sand content is applied, only three of the basins – Little Dalton, Big Dalton, and Santa Anita – intercept more than 10,000 cubic yards of sand per year.

Table 7.4 Debris Basins with Average Deposition Rates Exceeding 10,000 yd^3/year

DEBRIS BASIN	COUNTY	DEPOSITION RATE (YD^3/YR)
LITTLE DALTON	Los Angeles	22,643
BIG DALTON	Los Angeles	20,951
SANTA ANITA	Los Angeles	19,261
SIERRA MADRE VILLA	Los Angeles	18,221
SAWPIT	Los Angeles	15,228
LA TUNA	Los Angeles	14,750
VERDUGO	Los Angeles	12,738
GABBERT CANYON	Ventura	11,376
ADAMS	Ventura	11,271
PICKENS	Los Angeles	11,246
LIMEKILN	Los Angeles	10,917
ARUNDELL BARRANCA (OLD)	Ventura	10,888
ALISO	Los Angeles	10,003

The rates of debris interception by basins are highly irregular through time and space. The temporal distribution of severe rainstorms and the spatial and temporal distribution of fires make debris production forecasting difficult. Further, most of the debris accumulation data reported in the table above and in Appendix B are strongly influenced by one or two years of extreme data. These effects can be illustrated through an examination of data for debris basins in the Los Angeles River and San Gabriel River watersheds in Los Angeles County (Figure 7.13), based on the work of Barron (2001).

The combined capacity of the 85 debris basins in the Los Angeles River watershed totals 5,813,250 cubic yards, while the total for the 21 Basins in the San Gabriel River is 1,780,600 cubic yards. The average capacity of basins in the Los Angeles River drainage is about 68,000 cubic yards, and 85,000 cubic yards for the San Gabriel River drainage. As of 1997, the 85 debris basins of the Los Angeles River have experienced a combined number of storm seasons that totals 3,091 seasons (or years), or about 30 seasons per basin. Those in the San Gabriel River watershed combine for 620 seasons, or about 15 seasons per basin. Debris basins in the Los Angeles River watershed annually trap about 6,000 cubic yards of sediment per square mile of drainage area. The analogous rate for the San Gabriel River watershed is approximately 5,600 cubic yards per year per square mile. The basins of the Los Angeles River watershed each capture an average of about 3,200 cubic yards of sediment annually, and each basin in the San Gabriel River watershed capture nearly 3,400 cubic yards annually.

Figure 7.13 Distribution of debris basins in Los Angeles County in 1997.

A number of studies (e.g. Inman and Jenkins 1999) have indicated that, in Southern California, extreme precipitation events are responsible for sediment production that greatly exceeds average conditions. This can be seen in LACDPW data for maximum debris production years for its debris basins (Figure 7.14).

These maximum debris production events are closely associated with the large flooding events identified as peak episodes during wet periods by Inman and Jenkins (1999). Their study stated that this region experienced a dry period from 1944 to 1968 that was followed by a wet period from 1969 to 1995. Sediment yield increased with the number of dry, or low-flow, years that preceded a wet-year event due to the build-up of sediment within the watersheds (Inman and Jenkins, 1999). Most importantly, transport of sand-sized sediment, as opposed to clay or silt, escalated as streamflow increased.

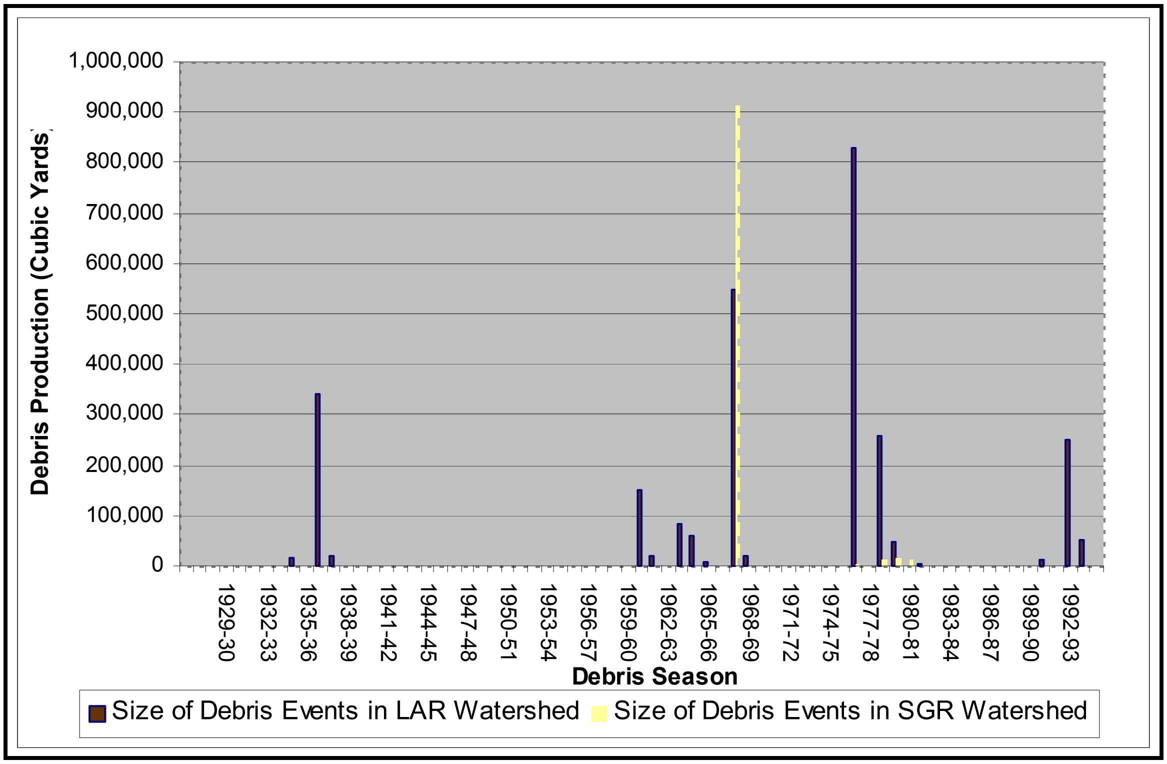

Figure 7.14 Distribution of maximum debris-producing events in the watersheds of the Los Angeles River (LAR) and the San Gabriel River (SGR)

Inman and Jenkins (1999) noted that the Los Angeles River had its highest yields of suspended sediment in 1969, 1978 and 1983, respectively, all during wet periods (Inman and Jenkins, 1999). Two of these years, 1969 and 1978, also had substantial accumulation of sediments in debris basins. The 1983 storm year may not have had significant sediment yield because it followed the 1978 storm that would have flushed much of the available sediment from the fluvial system.

The temporal distribution of maximum debris producing years is shown in Figure 7.14. The figure indicates the combined debris accumulation for the basins experiencing their maximum events in a particular year. For the Los Angeles River system, it can be seen that there are small peaks during the late 1930s when more than 350,000 cubic yards of sediment were deposited. These events were larger than the raw numbers might indicate because this trapping was accomplished by only 16 debris basins. These years represent the maximum debris production year for most of those sixteen basins. There also are noticeable peaks during the 1968-69 season (a maximum for 10 debris basins: 546,400 cubic yards deposited) and the 1977-78 season (a maximum for 27 debris basins: 829,855 cubic yards deposited). A small peak also occurred in the early 1990s; more than 300,000 cubic yards of sediment were deposited between late 1991 and early 1995. In terms of the quantity of debris production, 1978, 1969 and 1938 had the greatest sediment accumulation, respectively. Two of these three years matched maximum suspended sediment flux/yield years identified by Inman and Jenkins (1999). Debris was produced throughout the 1960s, prior to the 1969 onset of the wet period that was identified by Inman and Jenkins (1999).

Inman and Jenkins (1999) found that the greatest suspended sediment yields for the San Gabriel River occurred in 1983, 1980 and 1969. The 1968-69 debris season produced the greatest amount of sediment deposition, totaling 912,900 cubic yards for half of the 18 debris basins that reported a maximum debris year. This could be considered a "first flush" event that removed sediment that had accumulated for decades during the dry period (Inman and Jenkins, 1999). The remaining maximum debris events were spread from late 1977 to early 1982. Two of the three maximum debris accumulation years matched Inman and Jenkins' (1999) maximum sediment yield years for the San Gabriel River.

According to Barron (2001), maximum debris accumulation years in the Los Angeles River system accounted for about 2,719,000 cubic yards of the total basin accumulation of 11,752,000 cubic yards. This means that 23% of all accumulated debris was trapped during a maximum year. A normal seasonal deposition for a single basin is about 2,500 cubic yards in the Los Angeles River watershed, but the average for a maximum debris production year is about 34,000 cubic yards. Of the total of nearly 2,555,000 cubic yards deposited in the basins of the San Gabriel River watershed, 931,200 cubic yards (36%)were deposited during the maximum years. A normal seasonal deposition for a single basin is about 2,400 cubic yards in the San Gabriel River watershed, but the average for a maximum debris production year is about 52,000 cubic yards.

7.4 Channelized Streams

7.4.1 Impact of stream channelization on sediment supply

By definition, a stream is channelized when its bed has been straightened, smoothed or deepened to permit the faster flow of water (Bates and Jackson, 1984). In urbanized watersheds, rivers and streams are channelized for two key reasons: flood control and stream bank stabilization. Many studies have shown that urbanization produces a pronounced effect on flood hydrographs (Figure 7.15): the lag time between peak rainfall intensity and peak runoff decreases, the magnitude of flood peaks increase, and there is an increase in total runoff volume (Mount, 1995). The primary goal of stream channelization in urbanized watersheds is to disperse runoff from impermeable surfaces in a city as quickly and efficiently as possible in order to help prevent flooding (Mount, 1995).

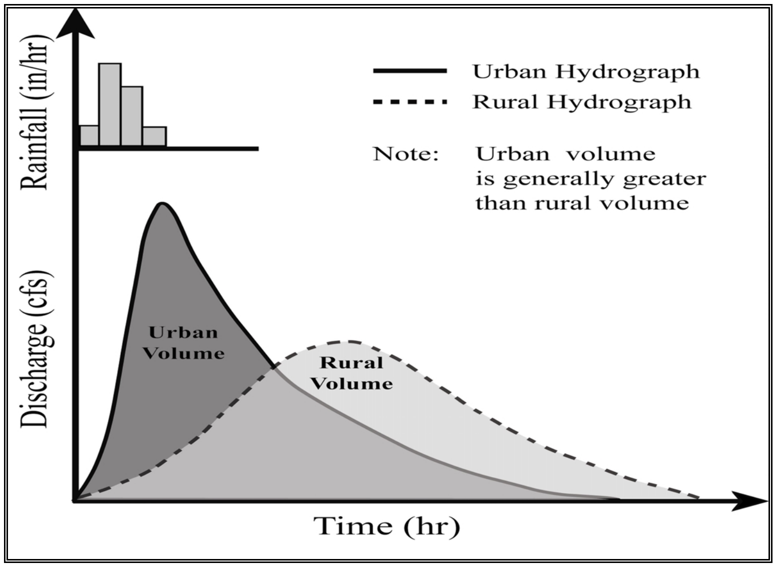

Figure 7.15 Hydrograph of urbanized watershed compared to rural watershed (From Mount, 1995)

Channelization in highly urbanized areas may take the form of excavation of streambeds and lining them with concrete (Plate 7.2) or spraying them with gunnite in order to decrease roughness. This increases flow velocities and impedes both downward and lateral erosion common to earthen (soft-bottom) channels (Mount, 1995). According to various researchers (Lane, 1937; Shen, 1971a; Richards, 1982), in order for an artificial channel excavated in natural sediment to remain stable, it must be able to transmit a bankfull discharge without experiencing bed or bank erosion (scour) or deposition of any sediment load from upstream. Often, this is not the case, and earthen channels tend to be unstable over time.

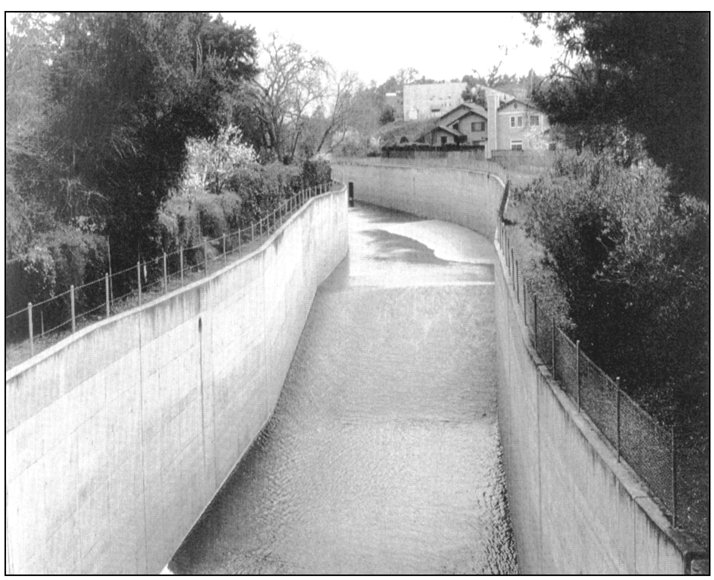

Plate 7.2 A channelized stream, deepened and lined with concrete (from Mount, 1995)

When artificial channels cannot transport the sediment load introduced upstream, deposition occurs within the channel and, in some cases, must be excavated. A concrete channel full of sediment is more prone to backup and flooding than an empty channel due to material slowing and disrupting the flow of water. This problem occurs in the county of Los Angeles, where the Department of Water and Power (LADWP) maintains 460 miles of channels (Plate 7.3). During the fiscal year of 1998 – 1999, the LADWP excavated 13,190 tons of sediment that had accumulated in their channels, and during the fiscal year of 1999 – 2000, they removed 43,809 tons of sediment (Table 7.5). The total amount of sediment removed varies greatly over time, but unfortunately these are the only two years for which the LADWP has accurate records as 1998-99 was the first year the department began using a computerized maintenance management system to track their work (personal communication – Jerry Burke, LADWP, Flood Maintenance Division).

Plate 7.3 *Los Angeles River flowing in a concrete channel* (from Mount, 1995)

Hard bottom channels not only are susceptible to problems of sediment deposition and removal, but also they prevent the downward and lateral erosion that naturally can supply beach-size material to the shoreline. Trimble (1997) found that stream channel erosion in San Diego Creek, which drains a 111 mile^2 (288 km^2) watershed in Orange County, has furnished about two-thirds of the total sediment yield, or 110,231 tons (100,000 tonnes) per year of sediment into Newport Bay. If this is the case for many Southern California streams and rivers, then constructing hard bottom channels cuts off an important supply of sediment to the coast.

Table 7.5 Summary of Stream Channelization and Channel Dredging in California

County	number of channelized streams	length of channelization in streams (miles)	volume of sediment removed from littoral system by channel excavation (yd^3/yr)
Del Norte	0	0	0
Humboldt	0	0	0
Mendocino	n.d.	n.d.	n.d.
Sonoma	1	n.d.	n.d.
Marin	3	n.d.	n.d.
San Francisco	n.d.	n.d.	n.d.
San Mateo	n.d.	n.d.	n.d.
Santa Cruz	2	4	n.d.
Monterey	n.d.	n.d.	n.d.
San Luis Obispo	n.d.	n.d.	n.d.
Santa Barbara	At least 4	n.d.	n.d.
Ventura	n.d.	n.d.	In 1978: 208,946 yd^3
Los Angeles	n.d.	460	Fiscal Year 1998-99: 10,782 yd^3 Fiscal Year 1999-00: 35,812 yd^3
Orange	Incomplete Data	n.d.	From 1972-77: 1,208,782 yd^3
San Diego	Incomplete Data	n.d.	n.d.

- *n.d. indicates no data were obtained.*
- *Information was provided at the county level, not the water-body level, so watersheds are undefined.*

7.4.2 Inventory of Stream Channels in Coastal Watersheds

In California, stream channelization in coastal watersheds is most relevant in the southern part of the state, where the population density is the greatest and the total length of channelized streams is the greatest. In Northern California, stream channelization is not an issue of concern due to lower population densities and a lack of large-scale urbanization.

Overall, the amount of information kept by county and city governments regarding the number of channelized streams within their jurisdiction, the length of channelization within those streams, the volume and grain size of sediment excavated and the final destination of that sediment is minimal. Workers in planning, engineering, public works, and flood control departments were contacted, or contact was attempted, for each coastal city and county. In many cases, replies were never made to phone messages or emails. When a contact was established, the contact often had no information or no time available to find the information requested. In some cases, contacts were very helpful; they searched for and supplied the data that were available (see Appendix C).

One reason that this investigation was largely unsuccessful in collecting data is that the organization of this information is at the county and city level. It appears that most local governments do not seriously track the removal of sediment from their channels. If local governments monitored and kept digital records of the sand content, average volume and final destination of excavated material, this investigation would have had greater success.

Given the lack of data available regarding channelized streams and sediment extraction from the stream channels, it is difficult to make any assessment of the significance of the volume of sediment removed from the littoral sediment system by these practices. The minimal data available on sediment extraction from the Los Angeles River channels (Table 7.5) show that, during fiscal year 1999-00, the total amount of excavated material was equal to about half of the average annual sand discharge of the river (Section 7.1, this report). The results from Trimble's work on San Diego Creek (1997) further suggest that a detailed investigation into the extent of stream channelization and channel dredging in coastal watersheds is warranted in order to assess whether or not alterations to these practices could yield an increase in sediment supply to the coast.

7.5 Prioritizing Sites for Sediment-Supply Intervention

In littoral cells where the value of beaches is substantial, beach erosion represents a significant economic loss (King, 1999). Where such losses are of a magnitude to threaten local economies, intervention to mitigate erosion caused by reduction of sediment supply may be desirable or necessary. Human activities have reduced substantially the supply of sediment to many littoral cells along the coast of California, especially in the central and southern parts of the state. For example, in Section 7.2.3 it was shown that fourteen reservoirs in Central and Southern California impound approximately 1,330,000 cubic yards of sand per year. On average, another 90,000 cubic yards of sand are trapped in the thirteen most productive debris basins, as discussed in Section 7.3. In some of the cells affected by these reductions, direct action to enhance sediment delivery to the beach may be justified. A challenge to the implementation of such strategies is the identification and prioritization of potential sites where sediment supply intercession would be most efficient. This section outlines a sample protocol for the identification of reservoirs and debris basins that might be candidate sites for sediment transport intervention.

7.5.1 A Protocol for Reservoir Identification

We have developed a simple method for identifying reservoirs that represent reasonable candidates for the development and application of policies to mitigate their impoundment of sediment. Other, more complex methods of identifying dams for management intervention might incorporate the economics of sand transport and assessments of impacts to riparian habitat, for example, on a site-specific basis; the protocol used here is just one example of a dam-identification methodology. The process began with data originally obtained from the National Inventory of Dams (USACOE, 1996) that describe dams that are at least 25 feet high and store at least fifty acre feet of water. About 1500 dams in California meet these criteria (e.g., Graf, 1999). Approximately one third of these dams (497) are in watersheds that drain directly to the coast (this definition excludes drainage through the Central Valley, for example). Many of these dams control discharge from large watersheds, but their net drainage areas – the area above a dam that is uncontrolled by other, upstream structures -- may be much smaller. Because most reservoirs are very efficient sediment traps (Collier et al., 1996), it can be assumed that virtually all sediment delivery to a particular reservoir will originate within the net drainage area. For the purpose of identifying a short list of dams where sediment impoundment might be substantial, it was decided therefore to consider further only those dams with a net drainage area of at least 36 square miles. The data in Table 7.6 indicate that the highest sediment production rates in the systems considered are more than 1,400 cubic yards per year per square mile of drainage. Multiplying 36 square miles of net drainage by 1,400 cubic yards per square mile per year yields an annual impoundment rate of about 50,000 cubic yards per year for a reservoir of this size. It was expected, therefore, that drainage systems smaller than about 36 square miles would rarely produce sediments at rates exceeding this value (although exceptions do occur, such as Devil's Gate Dam in Los Angeles County). We adopted this as a minimum annual accumulation rate to target a reservoir for further attention because this rate should generate about 25,000 cubic yards of sand per year. It is believed that smaller amounts probably would not represent substantial impacts to most California littoral cells, although larger or smaller rates might be appropriate for some coastal reaches. From the list of 497 dams in coastal watersheds, 53 dams met the net drainage area criterion (Figure 7.16).

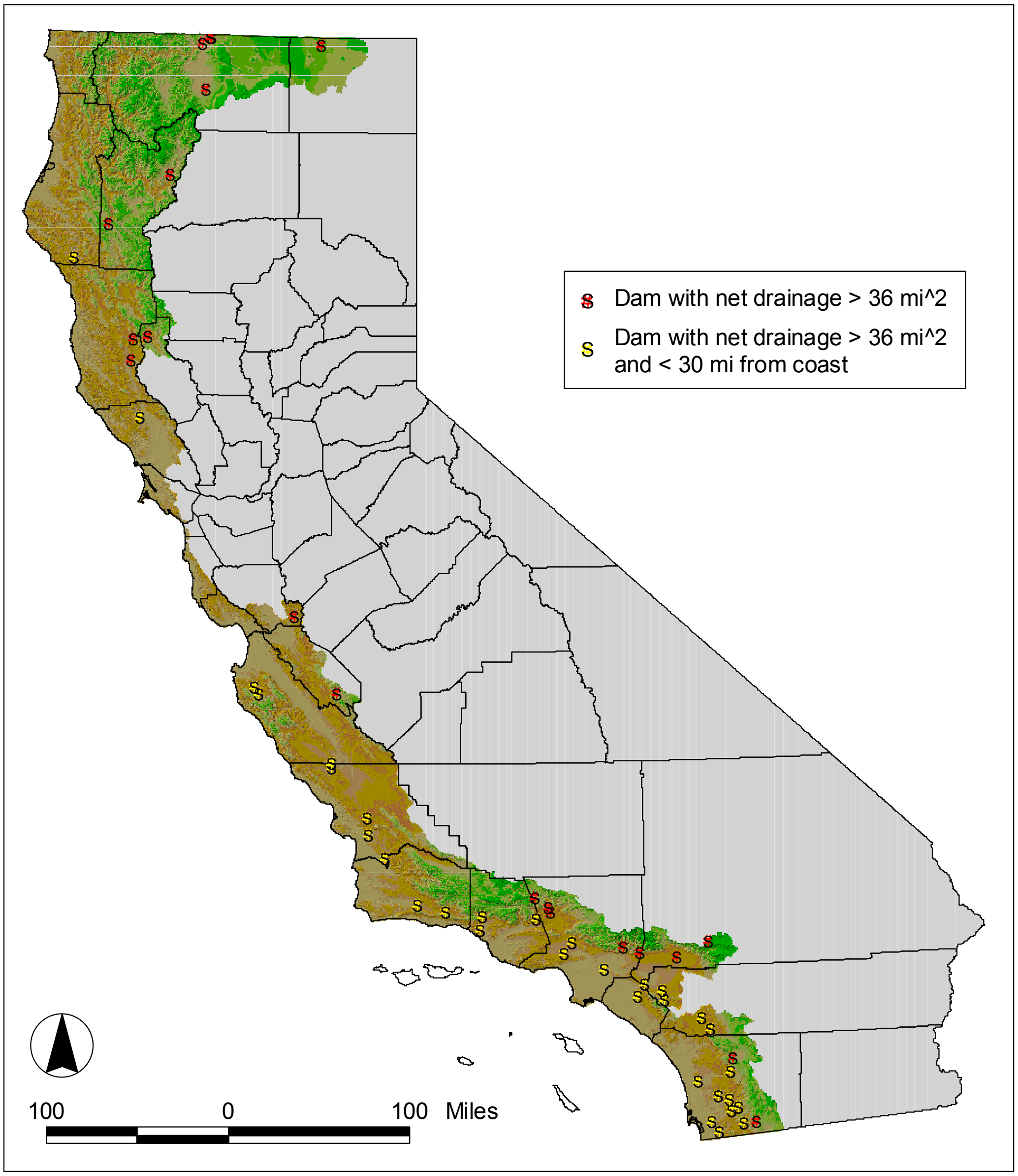

Figure 7.16 Locations of dams in California's coastal watersheds that control net drainage areas larger than 36 square miles

(Dams that are also less than 30 miles from the coast are highlighted)

Many of the 53 dams identified by the basin size criteria are far from the coast. Direct intervention in the sediment transport system, by physical movement of sediments via truck or sluice, for example, becomes economically impractical over long distances. We decided to apply a 30 mile limit to this distance. If a dam is located more than 30 miles from the coast, it was not considered further in this analysis. Larger or smaller distances may be appropriate cutoffs for some coastal reaches. Figure 7.17 shows the locations of the 53 dams that met the net drainage size criteria, and the subset of 32 dams that also met the distance-to-the-coast criterion.

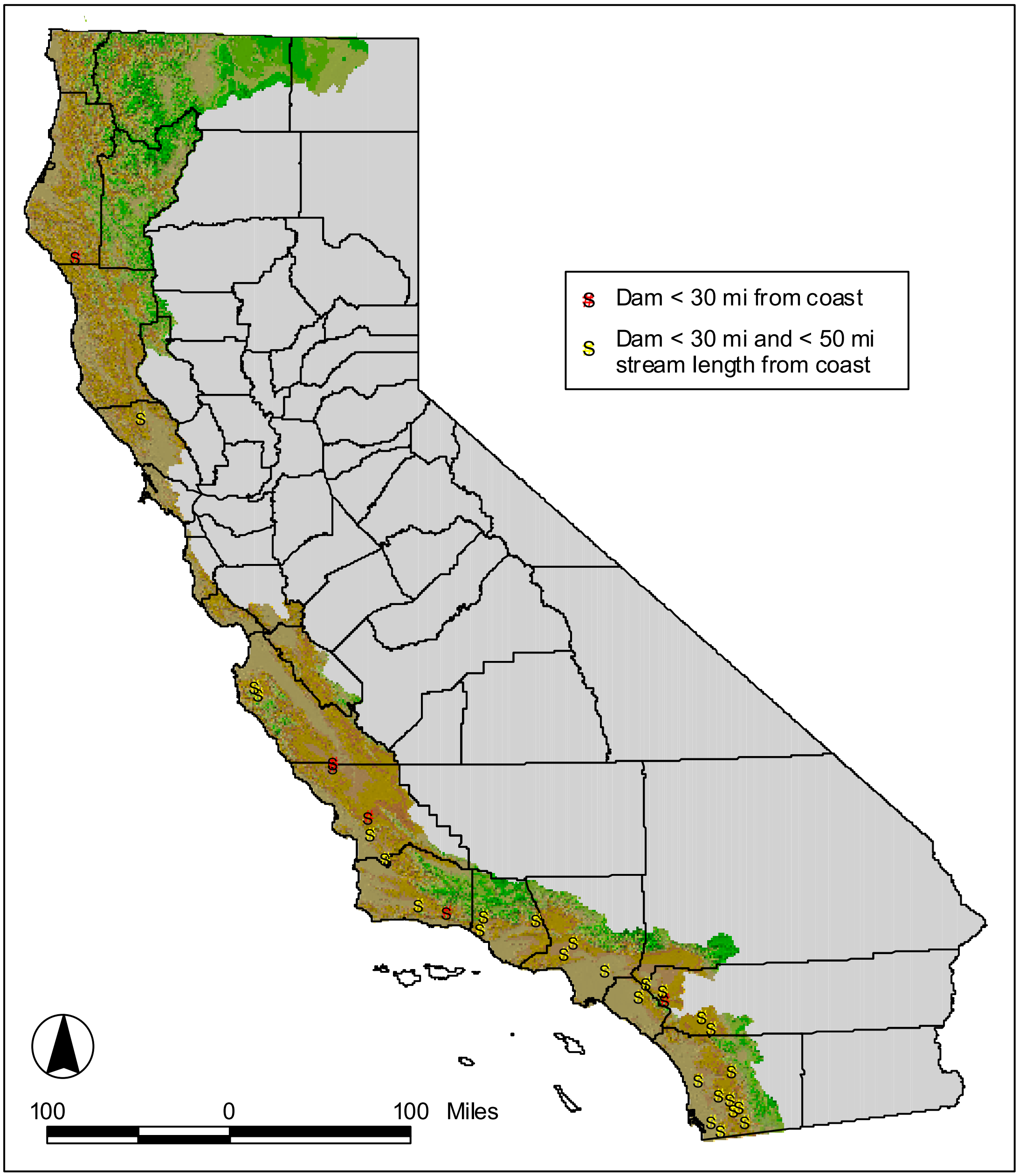

Figure 7.17 Location of dams with net drainage basins larger than 36 square miles, located less than 30 miles from the coast, with downstream channel lengths less than 50 miles

Another approach to restoring natural sediment supply is to partially or completely remove the impounding structure. Under some conditions, this approach may be the best solution to a number of complex environmental impacts associated with a particular structure (Task Committee on Guidelines for Retirement of Dams, 1997). However, we recognize that the release of sediments caused by dam removal (partial or complete) may have substantial and unpredictable negative impacts on downstream environments. Impacts include channel aggradation, changes in channel geometry and flow capacity, alteration of local habitat, and siltation (Hotchkiss et al., 2001). As a proxy for making river-specific impact assessments, given the lack of information needed to support such assessment, we assumed that the magnitude of the risk that substantial negative impacts would occur is related to the length of the fluvial system downstream of the dam being removed. Therefore, we applied a downstream distance criterion to the set of 32 dams described above. A dam was considered further only if the downstream distance separating the dam from the ocean is less than 50 miles. This procedure excludes dams such as Nacimiento and San Antonio that are located quite close to the coast when measured by straight line distance, but are well removed when measured by channel length. Figure 7.18 shows the locations of the 26 dams that meet all of the criteria described above.

The proximity to urbanized regions and the characteristics of the environment into which the respective fluvial systems drain were then examined for the remaining 26 dams. This review lead to the removal of another six structures from consideration: five in southern San Diego County, east of the City of San Diego (thus making physical transportation of sediments west to the coast through or around the city difficult), that also control drainage into San Diego Bay (where enhanced sediment delivery associated with sluicing or dam removal creates a sedimentation problem), and Warm Springs Dam, which controls drainage into the Russian River; the only beach in the vicinity of the mouth of the Russian River is a small barrier beach that does not appear to be at risk from erosion.

This method of prioritizing dams--in terms of their potential disruption of natural sediment transport processes and the ability to physically mediate the disruption--yields a set of twenty structures that may be suitable for sediment transport intervention. These structures and their characteristics are listed in Table 7.6. The locations of the structures are depicted in Figure 7.18.

This set of dams was then categorized according to the sedimentation data we obtained for each. Sedimentation data were not available for three of the dams: Casitas, Lopez, and Santiago Creek. Five of the dams exhibit minimal or no apparent sediment impoundment: Mathews, Robert A. Skinner, Sepulveda, Vail, and Whittier Narrows. The remaining twelve structures are priority sites for potential sediment transport intervention.

Table 7.6 Inventory of Dams Designated as Potential Priority Sites for Sediment Supply Intervention

(This designation is based solely upon net drainage basin size and distance from the coast.)

Dam	*County*	*Stream*	*Reservoir Capacity (yd^3)*	*Year of Last Survey*	*% Capacity Remaining*	*Sedimentation Rate (yd^3/yr)***
BRADBURY[1]	Santa Barbara	Santa Ynez River	330,665,000	2000	92%	580,000
CASITAS	Ventura	Coyote Creek	409,702,000	no data	no data	no data
EL CAPITAN[2]	San Diego	San Diego River	18,1946,400	1998*	96%	160,000
HANSEN[3]	Los Angeles	Tujunga Wash	41,044,398	1983	71%	420,000
LAKE HODGES[2]	San Diego	San Dieguto River	60,810,100	1994	91%	130,000
LOPEZ	San Luis	Arroyo Grande	84,682,500	no data	no data	no data
LOS PADRES[4]	Monterey	Carmel River	5,000,300	2000	67%	30,000
MATHEWS[5]	Riverside	Tr Cajalco Creek	293,566,000	n/a	100%	trivial
MATILIJA[6]	Ventura	Matilija Creek	2,903,400	1999	7%	200,000
PRADO[7]	Riverside	Santa Ana River	507,127,200	1996	86%	1,130,000
ROBERT A SKINNER[5]	Riverside	Tuucalota Creek	70,649,400	n/a	100%	trivial
SAN CLEMENTE[4]	Monterey	Carmel River	2,298,525	1996	10%	30,000
SAN VICENTE[2]	San Diego	San Vicente Creek	145,540,990	1998*	98%	40,000
SANTA FELICIA[8]	Ventura	Piru Creek	161,300,000	1996	87%	500,000
SANTIAGO CREEK	Orange	Santiago Creek	40,325,000	no data	no data	no data
SEPULVEDA[2]	Los Angeles	Los Angeles River	28,106,525	1980	100%	trivial
SUTHERLAND[2]	San Diego	Santa Ysabel	46,777,000	1998*	99%	10,000
TWITCHELL[1]	San Luis	Cuyama River	387,120,000	1999	71%	1,730,000
VAIL[9]	Riverside	Temecula Creek	82,263,000	n/a	100%	trivial
WHITTIER NARROWS[3]	Los Angeles	San Gabriel River	108,167,780	1977	97%	trivial

** preliminary survey data*
*** Method of calculating the sedimentation rate was not provided in source reports.*
[1] Source: Mr. Robert Wignot, General Manager, Cachuma Operation and Maintenance Board, 2001.
[2] Source: Ms. Rosalva Morales, Associate Engineer, City of San Diego Water Department, 2001.
[3] Source: Subcommittee on Sedimentation, 1992.
[4] Source: Mr. Andy Bell, District Engineer, Monterey Peninsula Water Management District, 2001.
[5] Source: Mr. Randy Whitney, Metropolitan Water District, 2001.
[6] Source: Mr. Charles Burton, Division Engineer, Ventura County Public Works Department, 2001.
[7] Source: Mr. Brian Tracy, Chief, Reservoir Regulation Section, U.S. Army Corps of Engineers, Los Angeles District, 2001.
[8] Source: Mr. Jim Kentosh, Senior Engineer, United Water Conservation District, 2001.
[9] Source: Mr. Craig Elithorp, Operations Manager, Ranch California Water District, 2001.

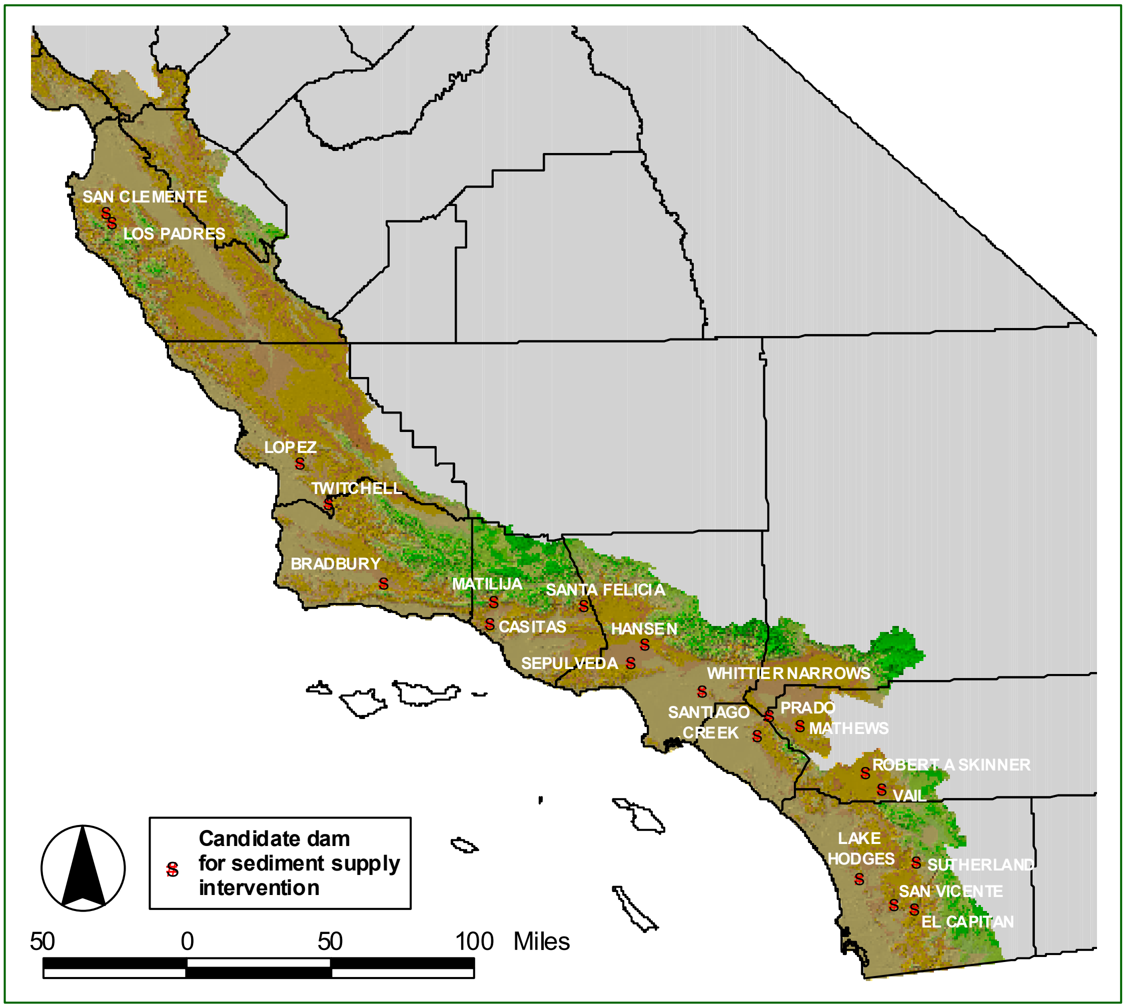

Figure 7.18 Location of dams of potentially high priority for sediment supply intervention

A dam is considered to impound a significant volume of sediment if its annual sedimentation rate exceeds 50,000 cubic yards, the reservoir capacity has been reduced by at least 25%, or both. Bradbury, El Capitan, Hansen, Lake Hodges, Prado, San Vincente, Santa Felicia, Sutherland, and Twitchell Dams all impound an average of at least 250,000 cubic yards of sediment per year (Table 7.6). For these reservoirs, the rationale for intervention to restore sediment transport would be based upon the magnitude of the disruption to the natural system. Los Padres, Matilija, San Clemente, and Twitchell Dams have all lost at least 25% of their capacity as a result of sedimentation. For these reservoirs, one rationale for intervention, which might take the form of removal or sediment bypassing, would be the restoration of capacity.

This approach to prioritizing reservoirs does not consider the grain size distributions of impounded sediments. This information is especially important when delivery of sand to the coast is the rationale for intervention, because sediments larger or smaller than sand size are not usually suitable for beach nourishment. The example of Twitchell Dam is illustrative. This dam has a very high impoundment rate (exceeding 1,500,000 cubic yards per year), and the reservoir capacity has been reduced by about 27%. From this perspective, Twitchell would seem like an ideal candidate for providing sediments for direct or indirect beach nourishment. However, the vast majority of these sediments is smaller than sand size – typically in the clay particle range – and therefore are not suitable for nourishment. There is very little grain size distribution data available for most California reservoirs. However, Taylor (1981) has provided some broad guidelines for the basin-level estimation of sand content (discussed previously). If the resulting sand impoundment rate (versus sediment impoundment rate) or total sand impoundment is still large relative to a downstream coastal sediment-budget deficit, then intervention for sediment-related reasons may be justified. In some cases, the need to restore fish passages might lead to removal of fluvial impediments as well.

Matilija is the only dam in this set that is a reasonable candidate for removal, and such action is presently in the planning stage. The water supply and flood control functions of the other structures would probably override the importance of a demand for beach sand in considering removal of the dams, though structures might be removed to improve fish passage. There are other constraints on particular dams and reservoirs that might inhibit the manipulation of sediment deposits. The flood control basin created by Prado Dam, for example, contains habitat for endangered bird species (Least Bell's Vireo; Tracy, 2001). Excavation of sediment from this basin would be difficult because of the potential disturbance of the habitat. Similar constraints may apply to other of the reservoirs listed here as priority sites. However, more research on the environmental characteristics of the individual systems is required.

7.5.2 A Protocol for Debris Basin Identification

The average debris basin traps about 1,000 cubic yards of sand-size sediment per year. During years with extreme sedimentation caused by wild fire and/or intense precipitation, accumulation rates may be an order of magnitude larger. For larger basins, however, the accumulation rates may average more than 10,000 cubic yards of sand per year, with extreme events generating substantially larger volumes of sand. In order to preserve the protective function of debris basins, these accumulations of sediment must occasionally be removed. When debris basins are cleaned, the excavated material may be a resource with beach nourishment potential if the volume and quality are appropriate.

There are about 200 debris basins in California. Most of them accumulate relatively little debris in an average year. They are widely dispersed, and many are in remote locations. Further, debris removal does not occur on a regularly-scheduled basis. Instead, the basins are cleaned when circumstances warrant. This suggests the need for a flexible protocol for the identification of debris basins from which excavated sediments can be beneficially used. The protocol is two-pronged, and is to be implemented when debris basin cleanout is planned to maintain storage capacity and the sediment to be removed has a substantial sand content. Under these conditions, a debris basin may be targeted as a direct or indirect source of material for beach nourishment. It is assumed that the costs of debris removal and loading onto trucks will have already been met, and that provisions have been made for the transport and disposal of the material. For basins near the coast, the protocol directs that the material be transported to a designated beach nourishment site. For sites farther from the coast, the protocol uses volume and quality of sediment to determine whether sand substitution is feasible. Under this protocol, construction-grade sediment may be sold, and the resulting revenue used to purchase and deliver sand to the beach from more efficient locales.

7.6 Discussion

In California each year, more than 1,500,000 cubic yards of sand-size material are impounded behind dams and within debris basins. Much of this material could and should be transported to the coast via natural or anthropogenic means. We have identified twelve dams for which the volume of sand that might result from intervention is substantial, especially in the context of local sediment budgets (Table 7.7). If sand were bypassed around these dams at the same rate as long-term average sand deposition in the reservoir, then bypassing could offset 40% of the sediment deficit in these Southern California littoral cells caused by sand impounded by dams.

We have outlined a general protocol for the identification and timing of exploitation of sand resources trapped in debris basins. These protocols were, however, developed in the absence of key information concerning the practical aspects of their implementation. In the context of managing sediment supply to California beaches, the impacts of individual debris basins are small, and it would be difficult or inappropriate to develop blanket policies to govern their management. The data presented in this report indicate the highly variable nature of sediment production and accumulation in the debris basin system in Southern California. Further, they also imply that alteration of debris basin management practices as a means of improving sediment supply to the California coast is probably only a reasonable endeavor when directed at infrequent, large debris production years. This is especially the case when recalling that only about 50% of the sediment retained by debris basins is of a size suitable for Southern California beaches. Finally, it is commonly assumed that all sediment trapped within debris basins ultimately would have been transported to the coast. However, the works of Brown and Taylor (1982) and Barron (2001) indicate that much of this debris would have been deposited across the alluvial plain in long-term sediment storage, and perhaps less than 20% of the debris total might have been delivered to the ocean over short time scales.

Table 7.7 Benefits of Dredging and Bypassing Activities at Dams Designated as Potential Priority Sites for Sediment Supply Intervention

Littoral Cell	Average Annual Sand Deficit[1] (yd³/yr)	Dam Name	Potential Sand Restoration[2]		Percent of Sand Deficit Restored by Bypassing
			Dredging[3] (Maximum One-Time Benefit, yd³)	Bypassing[3] (Average Annual Benefit, yd³/yr)	
Carmel River	45,558	Los Padres[5]	322,000	6,000	13
		San Clemente[5]	412,000	6,000	13
		Total	**734,000**	**12,000**	**26**
Santa Maria	624,671	Twitchell[5]	**14,194,000**	**346,000**	**55**
Santa Ynez	365,755	Bradbury[5]	**5,472,000,**	**116,000**	**32**
Santa Barbara	554,494	Matilija[5]	2,315,460	44,400	8
		Santa Felicia[5]	4,588,740	111,000	20
		Total	**6,904,200**	**155,400**	**28**
San Pedro	532,177	Hansen[6]	3,341,120	84,000	15
		Prado[6]	13,334,000	226,000	41
		Total	**16,675,120**	**310,000**	**56**
Oceanside	155,565	Lake Hodges[5]	2,132,000	26,000	17
		Sutherland[5]	92,000	2,000	1
		Total	**2,224,000**	**28,000**	**18**
Mission Bay	65,357	San Vicente[5]	456,000	8,000	12
		El Capitan[5]	2,112,000	32,000	49
		Total	**2,568,000**	**40,000**	**61**
TOTAL	**2,343,577**			**1,007,400**	**43**

[1] Data from Table 7.2
[2] Data are derived from volumes reported in Table 7.7 and Appendix A, assuming 20% sand
[3] Dredging assumes 100% recovery of sediment trapped in reservoir
[4] Assumes bypassing occurs at the same rate as long-term average sand deposition into reservoir
[5] Dam purpose is water supply
[6] Dam purpose is flood control

For the debris basins in Southern California, there are logistical obstacles to removing sediments and then reintroducing them into downstream fluvial or coastal systems. Some of these obstacles stem from environmental regulations that limit or prohibit the intentional deposition of sediments in active fluvial or coastal systems. Some obstacles stem from the difficulty and expense of removing and transporting sediment substantial distances to the coast. Other obstacles result from the temporal and spatial uncertainty in sediment production and impoundment.

It is clear that extreme sedimentation events, or the predicted occurrence of such events, will lead to the removal of sand-size material from debris basins. These events may create scenarios in which opportunistic beach nourishment is feasible. The requirement to dispose of sediments from debris basins for maintenance purposes already results in heavy vehicle traffic on foothill roads. Opportunistic beach nourishment requires only the funding necessary to transport sediments an additional distance to a pre-approved beach nourishment location.

It is recommended that policies be developed to facilitate the use of debris basin sediments for opportunistic beach nourishment. Such policies should encourage or require that sediments removed from debris basins, especially in response to extreme sedimentation events, be returned to the sediment transport system, preferably directly to the coast. Further, these policies should include anticipatory designation of nourishment sites, methods for beach nourishment (e.g., placing sand on a beach's berm, or grading onto the foreshore) and approved routes for heavy truck traffic. Alternatively, for excavation sites far from the coast, sediments could be sold for construction or fill purposes, and the revenues redirected to a regional beach nourishment account.

The development of such policies requires substantial additional research. More information is needed concerning the size distribution of sediments captured in some of the larger drainage basins and reservoirs. Sand content of sediments in some environments may be of insufficient volume to warrant aggressive approaches to sediment redistribution. Work is also needed to determine the location of a number of appropriate nourishment sites. Such determination may be based upon local erosion rates, wave energy climate (for the dispersal and reworking of nourishment sediments), or proximity to transportation arteries. Finally, at a larger planning scale, fundamental research into the influence of slope, precipitation, and fire on sediment production in watersheds is needed.

It is recommended that research be funded to describe environmental limits to sediment removal from individual reservoirs and debris basins. Research is needed on methods for separating the beach-compatible sand-size fraction from the rest of sediment impounded in reservoirs Finally, relatively little attention has been paid to how sediments can be delivered to the beach. Vehicular transport and the use of pipelines may be prohibitively expensive. Flushing materials downstream with natural or augmented flows may pose unanticipated environmental threats. Finally, it should be noted that most fluvial systems in California meet the ocean through an estuary. Any enhancement of sediment load in these streams will accelerate estuarine sedimentation, at least for time periods between large floods capable of flushing sediments to the sea. It is critical that research be conducted to understand and model potential effects so that undesirable negative impacts can be minimized.

7.7 REFERENCES

Andrews, E.D., 1986. Downstream effects of Flaming Gorge Reservoir on the Green River, Colorado and Utah. *GSA Bulletin*, Vol. 97: 1012-1023.

Barron, K.M., 2001. *Anthropogenic Alterations of Fluvial Sediment Supply to the San Pedro Littoral Cell of California.* Unpublished M.A. Thesis, University of Southern California Department of Geography. 130p.

Bates, R. L. and Jackson, J. A. 1984. Dictionary of Geologic Terms, Third Edition. Anchor Books. New York, NY. P, 82.

Bell, Andy, District Engineer for the Monterey Peninsula Water Management District, personal telephone conversation, 2001.

Best, T.C. and Griggs, G.B., 1991. A Sediment Budget for the Santa Cruz Littoral Cell, California. *From the Shoreline to the Abyss*. Society for Sedimentary Geology Special Publication No. 46, p. 35-50.

Biloki, Mike, 2001. Riverside County Flood Control District, personal communication.

Bohlander, M., 2001. Head, Hydrologic Engineering Section, Los Angeles County Department of Public Works, personal communication (cited in Barron 2001).

Bowen, A.J. and Inman, D.L., 1966. Budget of littoral sands in the vicinity of Point Arguello, CA. U.S. Army Coastal Engineering Research Center Tech. Memo. 19: 41pp.

Brown, W.M. and Ritter, J.R., 1971. Sediment Transport and Turbidity in the Eel River Basin, California. U.S. Geological Survey Water-Supply Paper 1986.

Brown, W. M. and Taylor, B. D., 1982. Inland artificial sediment movements. In, *Sediment Management for Southern California Mountains, Coastal Plains and Shoreline: Part D, Special Inland Studies*. California Institute of Technology Environmental Quality Laboratory Report No. 17.

Brownlie, W.R. and Taylor, B.D., 1981. *Sediment Management for the Southern California Mountains, Coastal Plains, and Shoreline, Part C: Coastal Sediment Delivery by Major Rivers in Southern California*. California Institute of Technology, Environmental Quality Lab Report No. 17-C, February 1981.

Brune, G.M., 1953. The trapping efficiency of reservoirs. *Transactions of the American Geophysical Union*. Number 34: 407-418.

Burton, Charles, Division Engineer in the Flood Control Agency of the County of Ventura Public Works Agency, personal telephone conversation, 2001.

California Department of Finance, *Historical City/County Population Estimates, 1991-2000, with 1990 Census Counts.* Sacramento, California, May 2000. http://www.dof.ca.gov/HTML/DEMOGRAP/HistE-4.htm.

California Department of Navigation and Ocean Development (DNOD), 1977. *Study of Beach Nourishment along the Southern California Coastline*. Department of Navigation and Ocean Development, State of California, The Resources Agency, October 1977, 149 pp.

California Rivers Assessment, 1992. California Resources Agency, http://endeavor.des.ucdavis.edu/newcara/

Campbell, R.H., 1975. *Soil Slips, Debris Flows and Rainstorms in the Santa Monica Mountains and Vicinity, Southern California*. U.S. Geological Service Professional Paper 851.

Capelli, M.H., 1999. Dam Sand Rights: Removing Rindge and Matilija Dams. Abstract in Sand Rights '99 Conference Proceedings.

Collier, M, Webb, R.H. and Schmidt, J.C., 1996. *Dams and Rivers: Primer on the Downstream Effects of Dams*. Tucson, Arizona, U.S. Geological Survey Circular 1126.

Collins, B.C. and Dunne, T., 1990. *Fluvial geomorphology and river gravel mining: a guide for planners, case studies included*. California Division of Mines and Geology Special Publication 98.

Cooke R.U., 1984. *Geomorphological Hazards in Los Angeles*. London, George Allen & Unwin.

DeVries, J.J, and Conard, S., 1991. *California Watersheds at the Urban Interface*. Proceedings of the Third Biennial Watershed Management Conference, University of California Water Resources Center Report 75, University of California, Davis.

Davis, M., 1998. *The Ecology of Fear: Los Angeles and the Imagination of Disaster*. New York, Vintage Books.

Division of Safety of Dams, 1998. Bulletin 17. http://damsafety.water.ca.gov/bltn17/bul17.txt

Elithorp, Craig, Operations Manager, Ranch California Water District, personal communication, 2001.

Environmental Protection Agency, 1998. Basins 2.0. http://www.epa.gov/ostwater/basins2_delete/gisdata.html

Ferrell, W.R., 1959. *Report on Debris Reduction Studies for Mountain Watersheds*. Los Angeles County Flood Control District, Dams and Conservation Branch.

Flick, R.E., 1993. The Myth and Reality of Southern California Beaches. *Shore and Beach*, Volume 61, No. 3: p.3-13.

Graf, W.L., 1999. Dam nation: A geographic census of American dams and their large-scale hydrologic impacts. *Water Resources Research*, Vol. 35: 1305-1311.

Grant, U.S., 1938. Geological Problems Involved in the Conservation of Beaches. Pacific Southwest Academy Publication 16, p. 27-28.

Griggs, G.B., 1987. The Production, Transport, and Delivery of Coarse-Grained Sediment by California's Coastal Streams. *Proceedings of Coastal Sediments '87*, Vol. 2. New York, American Society of Civil Engineers. p.1825-1838.

Geary, G., 2001. Fisheries Biologist, Pacific Gas & Electric. Personal communication, May 2001.

Hadley, R.F., Lai, R., Onstad, C.A., Walling, D.E., and Yair, A., 1985. *Recent Developments in erosion and sediment yield studies*. UNESCO Technical Documents in Hydrology: 127p.

Hotchkiss, R.H., M.E. Barber, and E.E. Wohl, 2001. Dam decommissioning: Decisions and unresolved sediment transport issues. *Proceedings of the Seventh Federal Interagency Sedimentation Conference*, Reno, Nevada, pp. 64-70.

Inman, D.L., 1989. Dammed rivers and eroded coasts. *Critical Problems Relating to the Quality of California's Coastal Zone*. San Francisco, California Academy of Sciences.

Inman, D.L. and Jenkins, S.A., 1999. Climate Change and the Episodicity of Sediment Flux of Small California Rivers. *Journal of Geology*, Vol. 107, p. 251-270.

Kaufman, W. and Pilkey, O., 1979. *The Beaches are Moving*. Anchor Press/Doubleday, Garden City, N.Y.: 326p.

Kentosh, James, Senior Engineer, Operations and Maintenance Department, United Water Conservation District, personal FAX communication, 2001.

King, P., 1999. *The Fiscal Impacts of Beaches*. San Francisco, Public Research Institute, San Francisco State University.

Kolker, O. C., 1982. Inland artificial sediment movements. In, *Sediment Management for Southern California Mountains, Coastal Plains and Shoreline: Part D, Special Inland Studies*. Environmental Quality Laboratory Report No. 17, Section D2, California Institute of Technology, Pasadena CA, p. 12-38.

Kondolf, G.M and Matthews, W.V., 1991. Management of coarse sediment in regulated rivers of California. University of California Water Resources Center Technical Report 748.

Knur, R.T., 2001. The Historical Sand Yield from Point Mugu to Santa Monica, California. Abstract in 2001 PACON Conference, San Francisco, June 2001:10p.

Lane, E. W. 1937. Stable Channels in Erodible Materials. *Transactions of the American Society of Civil Engineers*. 102. p. 123-94.

Leopold, L.B., 1968. *Hydrology for Urban Land Planning: A Guidebook on the Hydrologic Effects of Urban Land Use.* U.S. Geological Survey Circular No. 554.

Lewis, J., 1998. Evaluating the Impacts of Logging Activities on Erosion and Suspended Sediment Transport in the Casper Creek Watersheds. In *Proceeding of the Conference on Coastal Watersheds: The Casper Creek Story*, USDA Pacific Southwest Research Station General Technical Report, PSW-GTR-168, p. 55-69.

Meade, R.H. and Parker, R.S., 1984. Sediment in Rivers of the United States. In *National Water Summary 1984*. U.S. Geological Survey Water-Supply Paper 2775.

Morales, Rosalva, Associate Engineer, City of San Diego Water Department, personal communication, 2001.

Mount, J. F. 1995. *California Rivers and Streams*. University of California Press. Berkeley, CA. p. 287-302.

National Climate Data Center, 2001. http://www.ncdc.noaa.gov/ol/climate/climatedata.html#MONTHLY

Noble Consultants, 1989. Coastal Sand Management Plan. Contract report for BEACON, 186p.

Norris, R.M., 1963. Dams and Beach-sand Supply in Southern California. *Marine Geology*, Francis C. Shepard Commemorative Volume: p.154-171.

Richards, K. 1982. Rivers: Form and Process in Alluvial Channels. Methuen Inc. New York. NY. p. 276-271.

Ritter, J.R., 1972. Sand Transport by the Eel River and Its Effect on Nearby Beaches. U.S. Geological Survey Open-File Report, 17pp.

Rubin, D., 2001. Unpublished data for Colorado River below Glen Canyon Dam.

Santa Barbara County Flood Control & Water Conservation District and Water Agency, 1998. unpublished report.

Shen, H. W. 1971. Stability of Alluvial Channels. In Shen, H. W. (ed.) *River Mechanics*, vol. 1. Fort Collins, CO. p. 16.1-16.33.

Subcommittee on Sedimentation, 1992. *Sediment Deposition in U.S. Reservoirs: Summary of Data Reported 1981-1985*. Reston, Virginia: U. S. Interagency Advisory Committee on Water Data.

Task Committee on Guidelines for Retirement of Dams, 1997. *Guidelines for the Retirement of Dams and Hydroelectric Facilities*. New York, American Society of Civil Engineers.

Taylor, B.D., 1981. *Inland Sediment Movements by Natural Processes*. California Institute of Technology Environmental Quality Laboratory Report No. 17-B.

Topping, D.J., Rubin, D.M., and Vierra, L.E., 2000. Colorado river sediment transport: Natural sediment supply limitation and the influence of Glen Canyon Dam. *Water Resources Research*, Vol. 36., No. 2: 515-542.

Tracy, Brian, Chief of the Reservoir Regulation Section of the US Army Corps of Engineers, Los Angeles District, personal communication, 2001.

Trimble, S. W. 1997. Contribution of Stream Channel Erosion to Sediment Yield from an Urbanizing Watershed. *Science*. Vol. 278: p. 1442-1444.

Troxell, H.C., and J.Q. Peterson, 1937. *Flood in La Cañada Valley, California, January,1934*. U.S. Geological Service Water Supply Paper 796-C.

U.S. Army Corps of Engineers, 1996. *Water Control Infrastructure: National Inventory of Dams*. [CD-ROM]. Washington, D.C., Federal Emergency Management Agency

U. S. Geological Survey, 1999. *Water Resources Data for California*, Volumes 1 and 2. Water Data Report CA-99-1 and CA-99-02.

Ventura County Flood Control District, Hydrology Section, 1999. *Detention Dams & Debris Basins Manual*, revised June 1999.

Wells, W.G. II, 1981. Some effects of brushfires on erosion processes in coastal southern California. In, *Erosion and Sediment Transport in Pacific Rim Steeplands*, International Association Of Hydrological Sciences Publication 132, pp. 305-342.

Wells, H.G. II, and W.M. Brown III, 1982. D4: Effects of fire on sedimentation processes. In, *Sediment Management for Southern California Mountains, Coastal Plains and Shoreline: Part D, Special Inland Studies*. California Institute of Technology Environmental Quality Laboratory Report No. 17.

Whitney, Randy. Metropolitan Water District, personal communication, 2001.

Wignot, Robert, General Manager of the (Lake) Cachuma Operation and Maintenance Board, personal FAX communication, 2001.

Williams, G.P. and Wolman, M.G., 1984. Downstream effects of dams on alluvial rivers. U.S. Geological Survey Professional Paper 1286: 83p.

Wimenta, Tony, Flood Control Zone Coordinator, San Bernardino Department of Public Works, personal communication, 2001.

7.8 Glossary

bankfull discharge- The elevation of the water surface of a stream flowing at channel capacity.

bedload- sediment that is transported by rolling or bouncing along a river bed.

channelized stream: A stream whose channel has been straightened and / or deepened to permit water to flow faster.

debris flow- a moving mass of rock fragments, soil and mud, much more than half of which are larger than sand size. Slow debris flows may move less than 3 feet per year; rapid ones reach 100 miles per hour.

drainage basin- the land area that contributes water to or drains to a river system or body of water. Synonym: watershed.

fluvial- of or pertaining to a river

littoral cell- A segment of coastline that includes sand sources, alongshore transport or littoral drift, and then a sink or sinks for the sand; also known as a beach compartment.

runoff- Flow of water over the land surface that occurs when precipitation rates exceed the infiltration rates of water into the soil or when precipitation falls on impermeable surfaces. Runoff may occur as **sheet flow,** in which water moves as a film over the ground surface, or as **channelized flow**, in which water is organized into distinct rills, gullies, streams, and rivers.

sediment flux- the volume of sediment discharged by a river per unit of time, typically measured in English units as tons per day or cubic yards per day. Synonym: sediment discharge.

sediment yield- the volume of sediment discharged per unit area per unit time from a watershed, typically measured in English units as tons per acre per day.

streamflow- the volume of water of flowing past a given point per unit of time, typically measure in English units as cubic feet per second. Synonym: water discharge.

suspended sediment- sediment that is fully entrained or suspended in the water column.

water discharge- the volume of water of flowing past a given point in a given amount of time, typically measured in English units as cubic feet per second.

water year- a water year runs from October of the previous calendar year to September of the current calendar year.